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Advanced Turboprop Project

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Foreword

Because of the Middle East oil embargo in 1973 and the effects on the U.S. economy of fuel shortages, high prices, and dependence on foreign oil supplies, the U.S. Senate in early 1975 directed NASA to look at every potential fuel-saving concept that aviation technology could produce. Although several concepts were identified and pursued, the advanced turboprop promised the highest potential fuel saving for high-speed subsonic aircraft. It was, however, the most challenging concept technically and was initially resisted almost entirely by U.S. engine and airframe manufacturers, the airlines, and the military.

In spite of the challenges NASA decided to pursue the program because the potential payoff was too large to ignore. The Advanced Turboprop Project Office was formed at the NASA Lewis Research Center in Cleveland, Ohio, to manage and integrate the program. A systems approach was followed that looked at the entire aircraft in designing the propulsion system. This included elements such as the propeller and the nacelle, the drive system, installation aerodynamics, and the aircraft interior and community environments and the effect of these elements on meeting the goals of reduced fuel consumption, low operating costs, and passenger acceptance.

This approach followed a logic path that started with analyses and systems studies and proceeded to design code development based on scale-model wind tunnel tests or component tests. Large-scale systems were designed, ground tested, and ultimately flight tested as a proof of the concept. The technical expertise of all three NASA aeronautical research centers (Lewis, Langley, and Ames), more than 40 contracts distributed over the majority of the U.S. aircraft industry, and over 15 university grants were required to successfully complete the project. Major contract efforts were by General Electric on the Unducted Fan (UDF), Hamilton Standard on the Large-Scale Advanced Propfan (LAP), and Lockheed-Georgia on the Propfan Test Assessment (PTA).

In 1987 the advanced turboprop propulsion concept was proven by three flight programs using large-scale hardware. The NASA–General Electric–Boeing flight test and the General Electric–McDonnell Douglas flight test used the Unducted Fan as a proof-of-concept demonstrator for the gearless counterrotating concept. The NASA–Lockheed-Georgia Propfan Test Assessment test used the single-rotating, large-scale advanced turboprop to record verification data for propfan design codes. On the basis of the success of these tests and previous scale-model work Pratt & Whitney–Allison built a geared counterrotating propulsion system that they plan to fly on the MD–80 in early 1988.

These tests have demonstrated that the advanced turboprop uses 25 to 30 percent less fuel than equivalent-technology turbofan engines. The subsequent reduction in aircraft direct operating costs is 7 to 15 percent depending on fuel prices. The advanced turboprop has the required structural integrity and safety, aircraft interior environment, and community and enroute noise levels to be competitive with turbofan engines in commercial service. U.S. aircraft manufacturers plan to introduce new, highly efficient propfan-powered aircraft with vastly improved performance into the commercial fleet in the early 1990's.

This document provides a historical perspective of the Advanced Turboprop (ATP) Project and the technology that was developed to make the advanced turboprop a viable propulsion concept. Owing to the duration of the project and the number of technical challenges involved, only the major efforts have been covered. Some appreciation of the work accomplished in developing the turboprop concept can be acquired by looking at the bibliography.

G. Keith Sievers
Manager, ATP Project Office
1980–1988

Preface

From its inception aviation has been driven by the consistent desire to fly faster, farther, and higher. Achieving supersonic flight in the 1960's was viewed by many as the triumph of the century, a symbol of the United States technological superiority. But as the 1970's arrived, that perspective was altered. Environmentalists began raising concerns about air and noise pollution. Also a then-unknown force called the Organization of Petroleum Exporting Countries (OPEC) made Americans face the fact that energy sources were not unlimited and would not remain cheap. Lines appeared at fuel pumps and the compact, fuel-efficient car came into high demand. People learned to cope by traveling less, driving slower, carpooling, and using their air-conditioners and heaters more conservatively. The available solutions for airlines, however, were more severe. Cutting back on flights and increasing ticket prices meant losing business. The aircraft industry faced the possibility of surrendering its position as a world leader in the transport aircraft market.

At the direction of Congress NASA began exploring solutions to the aircraft fuel problem. In 1975 the NASA Inter-Center Aircraft Fuel Conservation Technology Task Force was formed to study every potential fuel-saving concept that aviation technology could produce. The result was the Aircraft Energy Efficiency (ACEE) Program targeted for implementation in fiscal year 1976. There were six major technological elements to this program. Three were airframe related (composite structures, active controls, and laminar flow control), and three were propulsion improvements (two for existing jet engines, and the third to develop the advanced turboprop).

The advanced turboprop concept promised the highest potential fuel savings, at least 30 percent, but was very challenging in the areas of propeller cruise efficiency, aircraft interior and environmental noise, installation aerodynamics, and maintenance costs. Because of this and the airlines' concern that customers would perceive the propfan as a "step backward" considerable opposition had to be overcome to proceed with its development.

Advocacy efforts were rewarded in 1978 when NASA formally began the Advanced Turboprop (ATP) Project. The project, managed by the Lewis Research Center, had the goal of establishing both single- and counterrotating propfan technology for Mach 0.65 to 0.85 applications. The ATP Project Office used a "systems" approach, which meant placing the work within the NASA aeronautical research centers, where the expertise existed. The Ames and Langley Research Centers provided facilities and expertise for studying and improving the aerodynamic interaction between the propulsion system and the airframe; Langley undertook the work of evaluating and attenuating the aircraft interior noise level; and Dryden Flight Research Center flight-tested small-scale propellers to evaluate in-flight propeller noise. The project was structured to resolve technical issues through code development and scale-model tests before ground and flight testing of large-scale systems. Because of funding limitations and to simplify the analysis, the preliminary work was directed toward single-rotating technology and was later extended to counterrotating systems.

From 1976 through 1986 wind tunnel tests were conducted on single-rotating scale-model propfans. Performance predictions based on early test results encouraged funding for counterrotating research. In 1983 Lewis let contracts with Hamilton Standard and General Electric to design and build counterrotating test rigs and to test scale-model propfan blade designs. These tests, conducted from mid-1985 through 1986, measured performance, acoustics, and aeromechanical stability in NASA wind tunnels and in contractor tunnels and anechoic chambers.

The Lewis ATP Project included large-scale ground and flight testing to validate propfan blade acoustics, structures, and performance. In 1983 General Electric proposed a similar program for a gearless, counterrotating pusher engine, the Unducted Fan (UDF). Early in 1984 Lewis agreed to support an effort with General Electric to design and ground test a proof-of-concept engine in order to demonstrate the suitability of the counterrotating concept for commercial applications.

Ultimately the ATP Project resulted in three series of flight tests: the UDF tests on a Boeing 727 in 1986–87 as a commercial demonstration; Propfan Test Assessment (PTA) single-rotating tests in 1987 to validate design data; and the UDF tests on a McDonnell Douglas MD–80 in 1987, also as a commercial demonstration. Encouraged by the results of the ATP Project, Pratt & Whitney–Allison built a geared counterrotating pusher engine based on the design data acquired in Lewis-funded Allison gearbox and Hamilton Standard–United Technologies Research Center (UTRC) model tests. Although no Government funding was used to design or build this engine, its flight test on the MD–80 in early 1988 will be a further verification of the advanced turboprop concept.

As a result of their work the Lewis Research Center and the entire NASA/industry advanced turboprop team were awarded the 1987 Collier Trophy. The citation reads as follows:

> For developing advanced turboprop propulsion technology for new fuel efficient subsonic aircraft propulsion systems.

Acknowledgments

The Advanced Turboprop Project Office wishes to thank the personnel of the Lewis ATP Project for their contributions in preparing this document and Benjamin Thompson of the Sverdrup Corporation for his work in developing the text. Thanks are also in order for the people at Lewis, Langley, and Ames, General Electric, Pratt & Whitney, Allison, Hamilton Standard, Lockheed, McDonnell Douglas, Boeing, and all the other airframers, engine companies, and airlines whose time and efforts made the development of the advanced turboprop possible. Special thanks to Donald L. Nored, James L. Dugan, Daniel C. Mikkelson, and G. Keith Sievers of Lewis and Dr. Raymond S. Colladay and his staff at NASA Headquarters, who kept turboprops alive and well in spite of the resistance they encountered.

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Overview of Advanced Turboprop Project

Early History of Propellers

Propeller technology advanced steadily until the turbojet engine was developed in the late 1950's. Because propeller blades with adequate structural reliability were unable to overcome compressibility losses at the high speeds promised by the turbojets, the propeller began to lose favor and the aviation industry plunged wholeheartedly into developing jet propulsion technology.

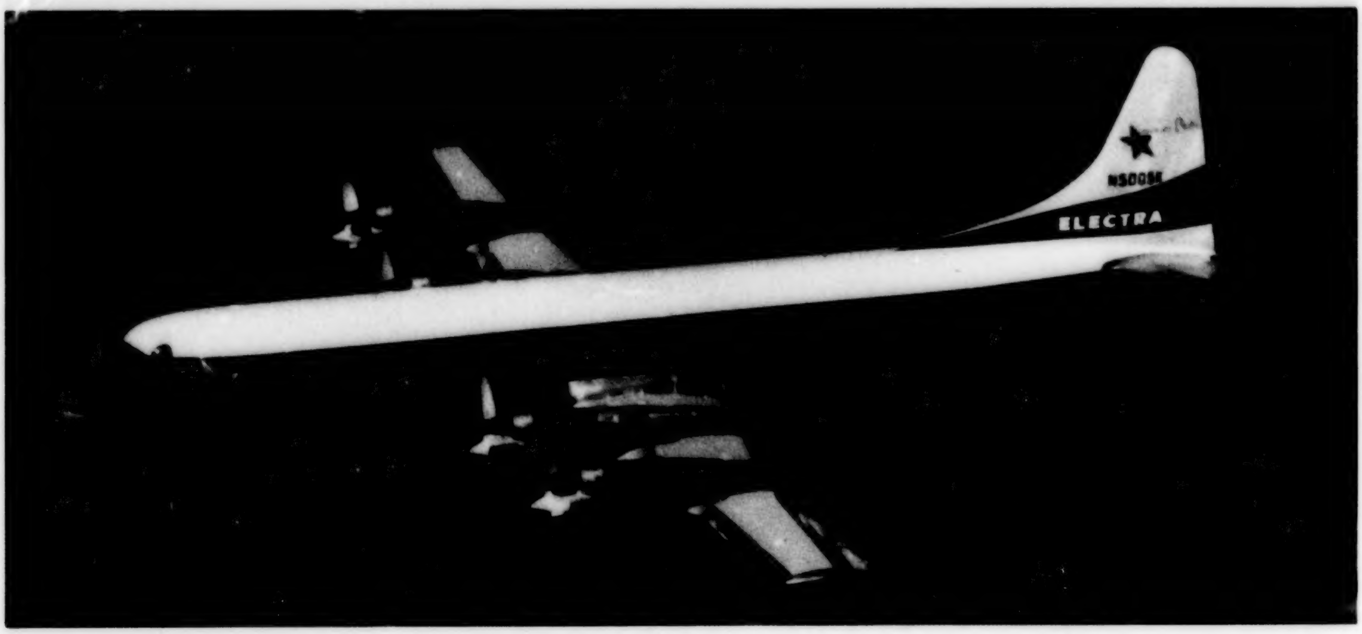


Figure 1.—Lockheed Electra.

With the tremendous speed advantage of jet propulsion, airlines disregarded the fact that propellers, such as those on Lockheed's Electra (fig. 1), were the more efficient method of propulsion at speeds to Mach 0.6. With fuel prices at 10 to 13 cents a gallon, the larger amount of fuel that turbojets and turbofans required seemed inconsequential in comparison with the quieter cabins and the greater speed, altitude, and distance that they promised. So in 1958, with the aircraft industry and NASA looking toward a future of high subsonic and supersonic transport, propeller research ended.

In 1973, however, perspectives changed again. Fuel shortages resulting from the Middle East oil embargo tripled fuel prices and disrupted airline service. Fuel costs, which had previously made up only a small portion of operating costs, soon accounted for almost half of an airline's budget. Suddenly fuel efficiency, which had long taken a backseat to the goals of increased speed, altitude, and distance, was now a most urgent concern. Government and industry groups sought to identify methods of reducing the fuel consumption of existing aircraft and engines.

Reinventing the Propeller

Engineers at Lewis were aware of the propeller's high efficiency. From 1927 to about the mid-1950's NACA, the predecessor to NASA, had an extensive propeller research effort. Data had been recorded in the 1930's for variable-pitch propellers; in the 1940's for highly loaded four- and eight-blade propellers, some of which had swept tips; and in the 1950's for thin propeller blades. Always the goal was higher speed and efficiency.

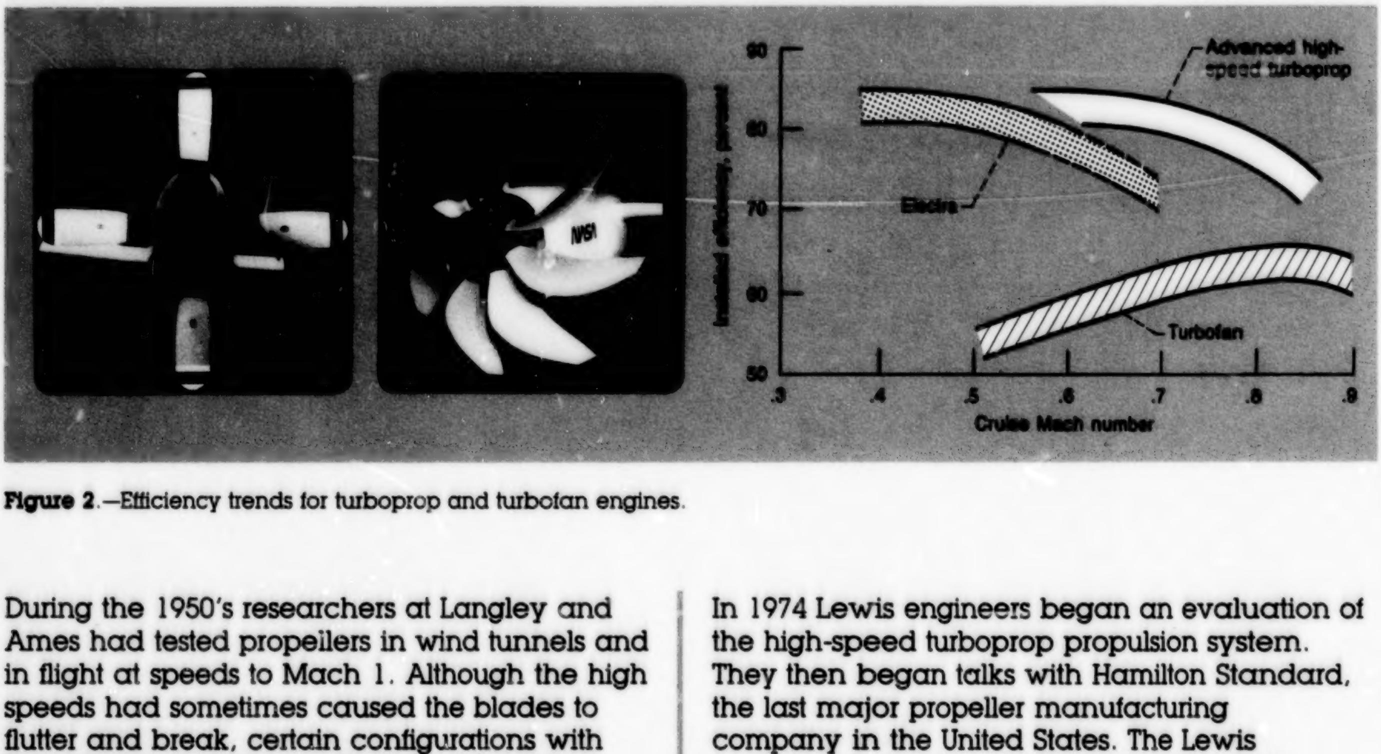


Figure 2.—Efficiency trends for turboprop and turbofan engines.

During the 1950's researchers at Langley and Ames had tested propellers in wind tunnels and in flight at speeds to Mach 1. Although the high speeds had sometimes caused the blades to flutter and break, certain configurations with thin blades and low loadings had exhibited high efficiency to Mach 0.85. This evidence that a propeller could maintain efficiency at high speed, combined with progress in computational aerodynamics and structural mechanics acquired from 20 years' experience in designing supersonic wings, helicopter rotors, and fan blades, gave Lewis engineers confidence that the propeller was a viable fuel-saving concept.

In 1974 Lewis engineers began an evaluation of the high-speed turboprop propulsion system. They then began talks with Hamilton Standard, the last major propeller manufacturing company in the United States. The Lewis engineers hoped to use the company data base as a foundation for an advanced turboprop concept. After much discussion Lewis and Hamilton Standard engineers concluded that a highly loaded, multiblade, swept, variable-pitch propeller, which they called the propfan, could be combined with the latest in turbine engine technology.

The resulting advanced turboprop would offer a potential fuel saving of 50 percent (fig. 2) over an equivalent-technology turbofan engine operating at competitive speeds and altitudes because of the turboprop's much higher installed efficiency.

Even with this potential the advanced turboprop met with strong resistance. At an American Institute of Aeronautics and Astronautics workshop on aircraft fuel conservation in March 1974 the advanced turboprop received strong disapproval from some key persons in industry and Government. This disapproval resulted from the poor operational experience (failures and short service life) demonstrated by reciprocating-engine-powered aircraft and by the gearboxes of some turboprop systems. A number of people felt so strongly about this issue that they stated that never again would a commercial aircraft be powered by a propeller. In spite of this opposition the interest in the advanced turboprop continued to grow because of its large potential fuel saving and because of the strong advocacy of both Lewis and Hamilton Standard engineers.

In support of the advanced turboprop Lewis engineers conducted several in-house system studies in 1974 and 1975 to determine benefits and to identify key technology issues. They used the older NACA test results for lightly loaded, thin-blade propellers but extrapolated them analytically to much higher disk loadings. The studies showed that an advanced turboprop could have efficiencies close to 80 percent at cruise speeds of Mach 0.8. As a result Lewis included advanced turboprops in the unconventional engine studies performed under contract by Pratt & Whitney and General Electric. These studies confirmed the fuel-saving potential previously determined by analysis and added strength to the arguments being made by Lewis and Hamilton Standard engineers in favor of the advanced turboprop.

Kramer Commission

While Lewis was exploring its solution to the fuel problem, Congress was busy looking for answers too. In January 1975 the Senate Committee on Aeronautical and Space Science under Senators Moss and Goldwater requested that NASA develop a program to address the fuel crisis.

In response NASA formed the Intercenter Aircraft Fuel Conservation Technology Task Force composed of scientists and engineers from NASA, the Department of Transportation, the Federal Aviation Administration, and the Department of Defense. The task force, headed by NASA's James Kramer, received a mandate to look at every potential fuel-saving concept that aviation technology could produce. Although working for advances in turbofan and turbojet engines seemed an obvious path to follow, Kramer asked the NASA research centers, major airframe and engine manufacturers, and other Government agencies for any and all ideas, even those that might be considered unusual. Lewis engineers submitted the advanced turboprop concept. Through their efforts the advanced turboprop was given serious consideration by some task force members. Kramer contacted Hamilton Standard engineers for their assessment and received their support. The task force continued throughout 1975 to plan each technology development, to estimate costs and fuel savings, and to project major milestones. The program the task force proposed was the Aircraft Energy Efficiency (ACEE) Program, targeted for implementation in fiscal year 1976. Included were six major technological projects. Three were airframe related—researching composite structures, developing practical active controls, and using laminar flow control. The other three were propulsion related. Predictably two aimed at improving existing jet engines and developing new ones. But the third, more controversial, project was to develop advanced turboprops.

All three propulsion projects came to Lewis. The Engine Components Improvement (ECI) Project was begun first. It involved improving existing engine components by using improved aerodynamics and materials, applying clearance control techniques, and increasing the bypass ratio—for a projected fuel saving of 5 percent. It was followed by the Energy Efficient Engine (EEE) Project, which incorporated the best fuel-saving technologies in the new engine designs—for a projected fuel saving of 15 to 20 percent. For both projects the results exceeded the goals and many of the design features have been included in models of JT8D, JT9D, CF6, and CFM-56 engines being produced by Pratt & Whitney and General Electric.

The advanced turboprop concept promised the highest potential fuel saving, 50 percent or better (fig. 3) if improvements in core engine technology were included. However, it was the most challenging concept both technically and politically. Because there was still some opposition, only very limited funding was provided and additional studies had to be performed to support the value of the advanced turboprop and to identify the most critical technical issues. The Reduced Energy for Commercial Air Transports (RECAT) studies by Boeing, McDonnell Douglas, and Lockheed indicated that the advanced turboprop had the highest potential payoff of any element in the ACEE Program but identified several areas of technical concern (propeller efficiency at cruise, propeller and aircraft interior noise, installation aerodynamics, and maintenance costs). An engine, gearbox reliability, and maintenance cost study by Allison and Hamilton Standard responded to one of the chief industry concerns by showing that the higher maintenance costs and lower reliability of past turboprop engines were largely due to the older technology of the core engines. In addition, improved gearbox designs would substantially lower maintenance costs and improve reliability. These results plus previous studies showing the fuel efficiency benefits of the turboprop led to greater acceptance by the airlines. The possibility of lower ticket prices due to reduced operating costs lessened the airlines' concern that customers would perceive the turboprop as a "step backward."

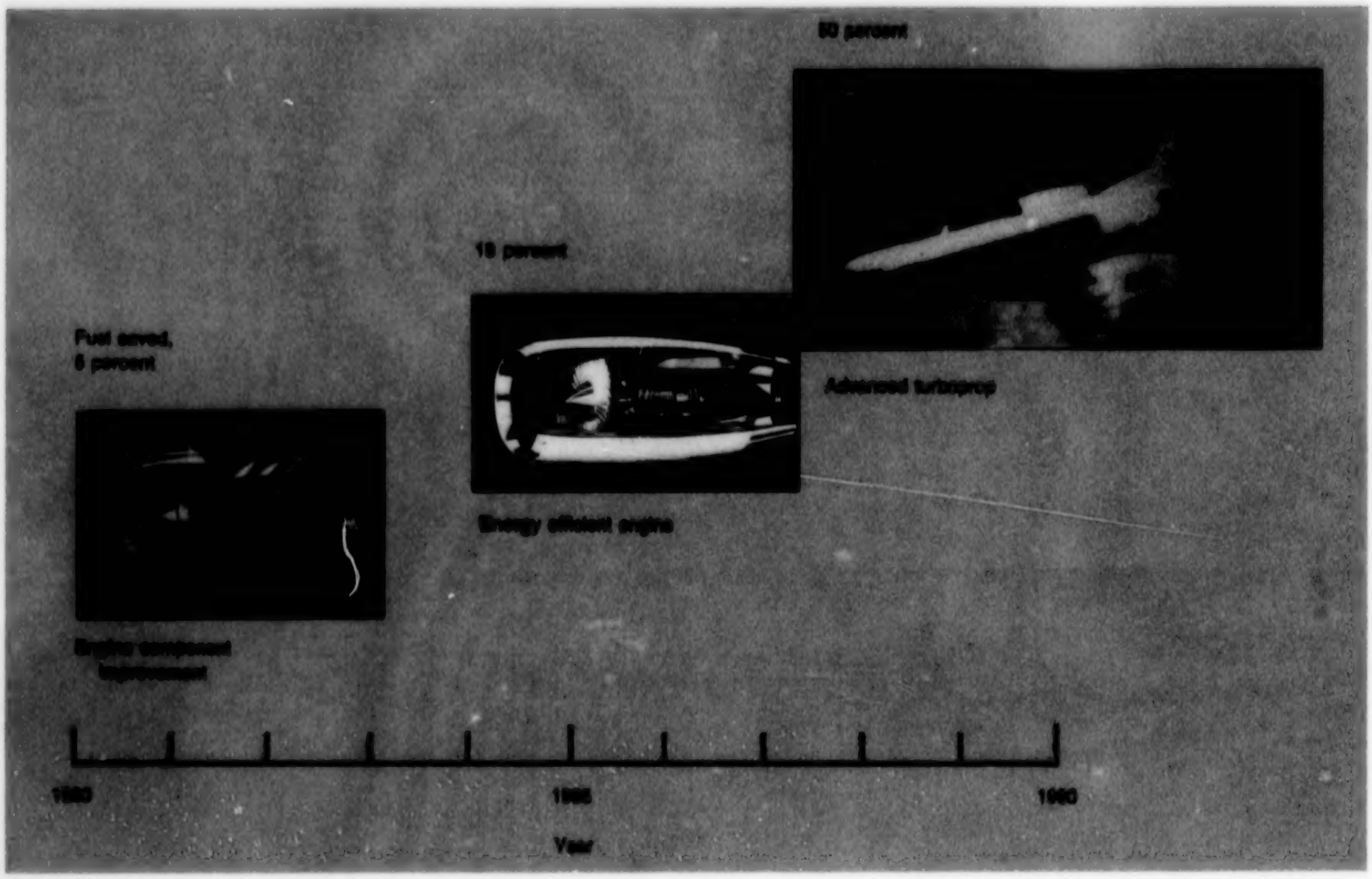


Figure 3.—Three propulsion projects in Aircraft Energy Efficiency Program.

Proving the Propfan's Potential

Lewis researchers knew that first they had to prove that the propfan was as efficient as they believed it could be. Therefore they awarded a contract in April 1976 to Hamilton Standard for the design, fabrication, and testing of a 2-foot-diameter propfan model.

Design of the SR–1

Engineers at Hamilton Standard and Lewis considered two approaches to designing the turboprop's propeller—a single-rotating propfan, consisting of one row of blades; and a counterrotating propfan, consisting of two rows of blades rotating in opposite directions. Because of budget limitations and the complexity of the counterrotating configuration, they chose to begin with a single-rotating model to prove the concept. They called this initial design the SR–1, for single-rotating model 1 (fig. 4).

The design and performance of this model were vital to the advocacy of a large turboprop program and to its ultimate success. A high cruise efficiency had to be attained to support the large projected fuel saving claimed for turboprops and thus quiet some of the vocal opposition. To ensure achievement of a successful design, Lewis and Hamilton Standard undertook a cooperative effort to best use the expertise of their engineers.

Since efficiency at high speeds was the key to success, the designers of the SR–1 tried to incorporate every possible means of reducing compressibility losses. They selected better airfoils and designed blades with thickness-to-chord ratios that were roughly half those of the most advanced conventional propellers. To reduce diameter and to ease aircraft installation, they used higher power loadings. To keep the individual blade loading reasonable, they increased the number of blades to eight. To reduce root choking, a problem caused by the higher hub solidities that accompanied the extra blades, they decided to integrate the design of the propfan with the design of the nacelle and spinner so that the hub flow velocity between the blade roots could be reduced (figs. 5 and 6).

Knowing how successful sweep had been in reducing compressibility losses in wings, they designed the SR–1 with blade tips that had 30° of sweep. An added benefit of sweep was the potential decrease in the noise levels resulting from the high blade tip speed. Sweeping the blade tip delays to a higher relative helical tip Mach number the sharp rise in drag and noise that occurs when the airflow over the blade resulting from both airplane forward speed and propeller rotational speed approaches Mach 1.

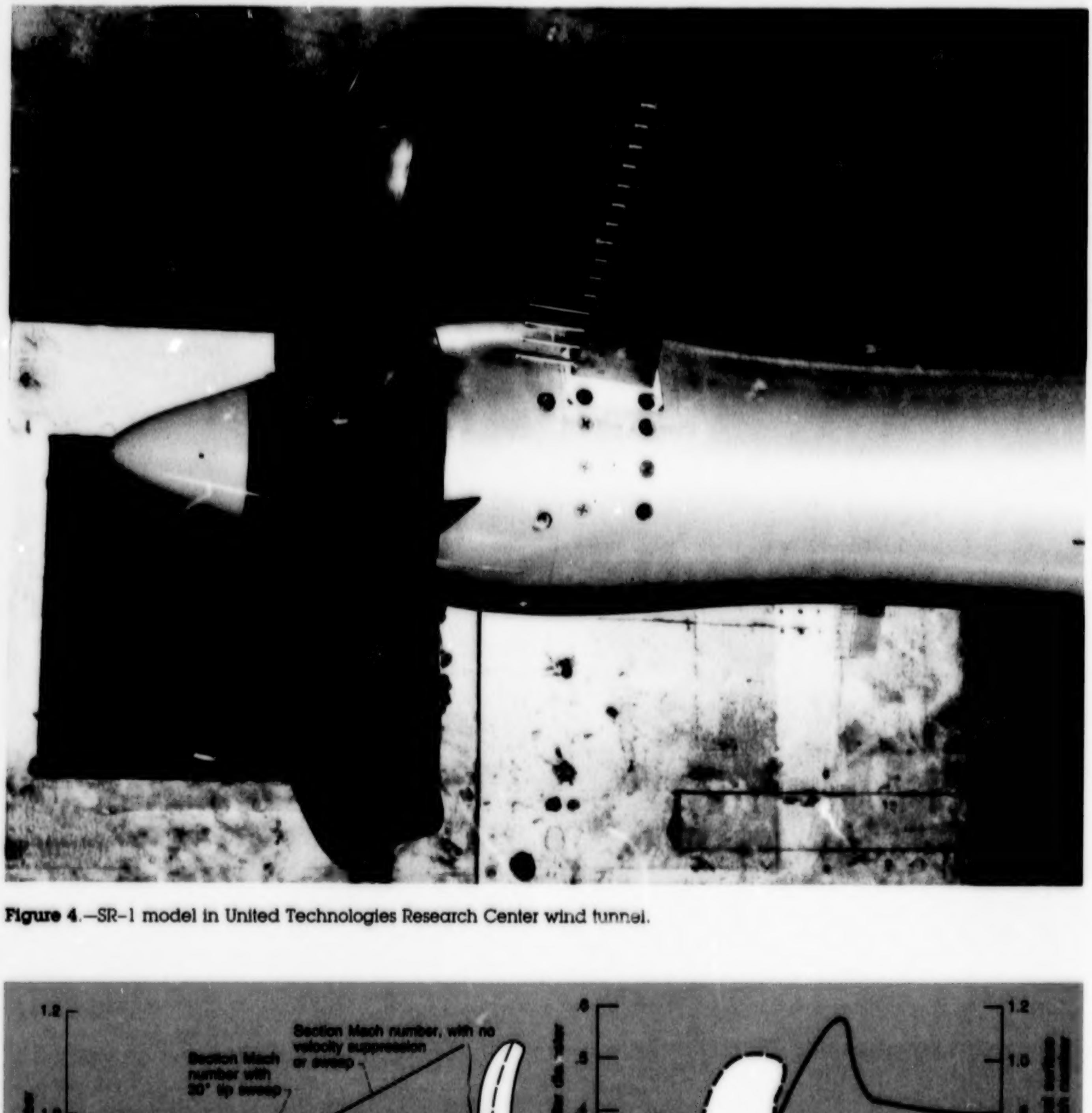


Figure 4.—SR-1 model in United Technologies Research Center wind tunnel.

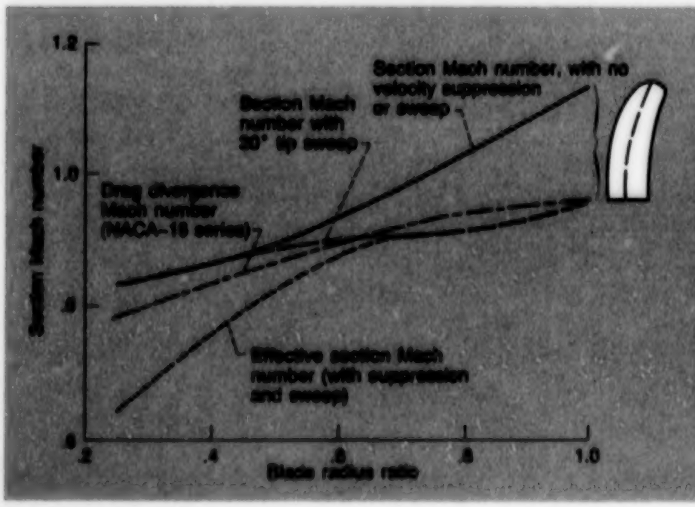


Figure 5.—Design improvements to reduce section Mach number.

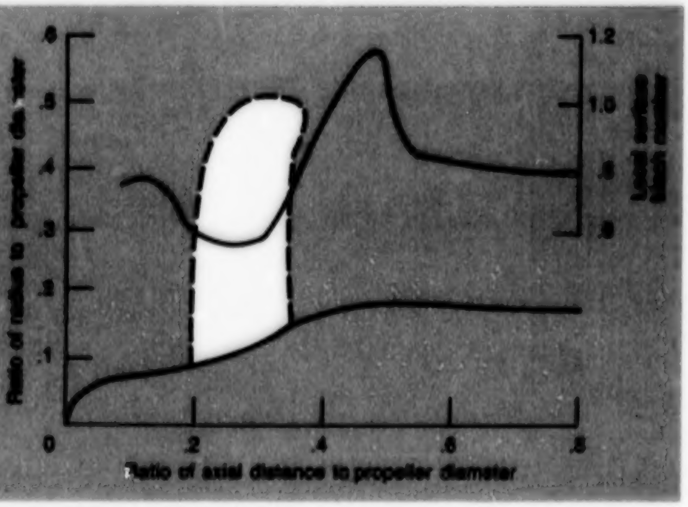


Figure 6.—Effect of spinner contouring on reducing section Mach number.

Hamilton Standard Wind Tunnel Performance Tests

The SR–1 aerodynamic design and performance testing in the United Technologies Research Center (UTRC) wind tunnel was the first major milestone in the ATP Project. The objective of these tests was to investigate how sweep affects propfan performance and noise at speeds to Mach 0.8.

The SR–1 achieved an efficiency of 77 percent at Mach 0.8, very near the goal, and the model blades were stable even when the researchers tried to force flutter. The changes in radial thickness distribution dictated by the structural codes plus the use of titanium instead of steel blades prevented the flutter problems that had limited the tests performed by Ames and Langley during the 1940's and 1950's. Encouraged by this but still needing to fully understand the efficiency and noise potential of the propfan, Hamilton Standard designed several more models under contract to Lewis.

One was a modified version of the SR–1, called the SR–1M. Its twist distribution was modified spanwise to better distribute the blade loading. This resulted in a 1-percentage-point gain in overall efficiency. Another model, the straight-blade SR–2, was designed to provide a baseline for comparison between a straight and a swept blade. Its efficiency was slightly less than 76 percent at Mach 0.8.

The last model tested was the SR–3 (fig. 7), which incorporated 45° sweep for both aerodynamic and acoustic purposes. It achieved an efficiency of nearly 79 percent, almost 3 percentage points better than the unswept SR–2 in tests at both UTRC and Lewis. The results of these tests supported the performance levels predicted by Lewis and provided a basis to press for further funding of the turboprop as one of the engine concepts in the ACEE Program.

Lewis engineers recognized early in planning the high-speed turboprop research program that counterrotating propellers could further improve performance. The highly loaded single-rotating propfans had an efficiency loss of 6 to 8 percentage points due to residual swirl. Most of this loss could be recovered with a well-designed counterrotating propfan. The potential benefits of counterrotating propfans were studied in-house at Lewis and on contract by a team from Hamilton Standard and Pratt & Whitney. On the basis of the favorable study results Lewis engineers recommended to NASA Headquarters that a counterrotating propfan model program be started, but Headquarters was able to provide only limited funding. This funding was used to start a small, long-lead-time task to develop a counterrotation aerodynamic analysis.

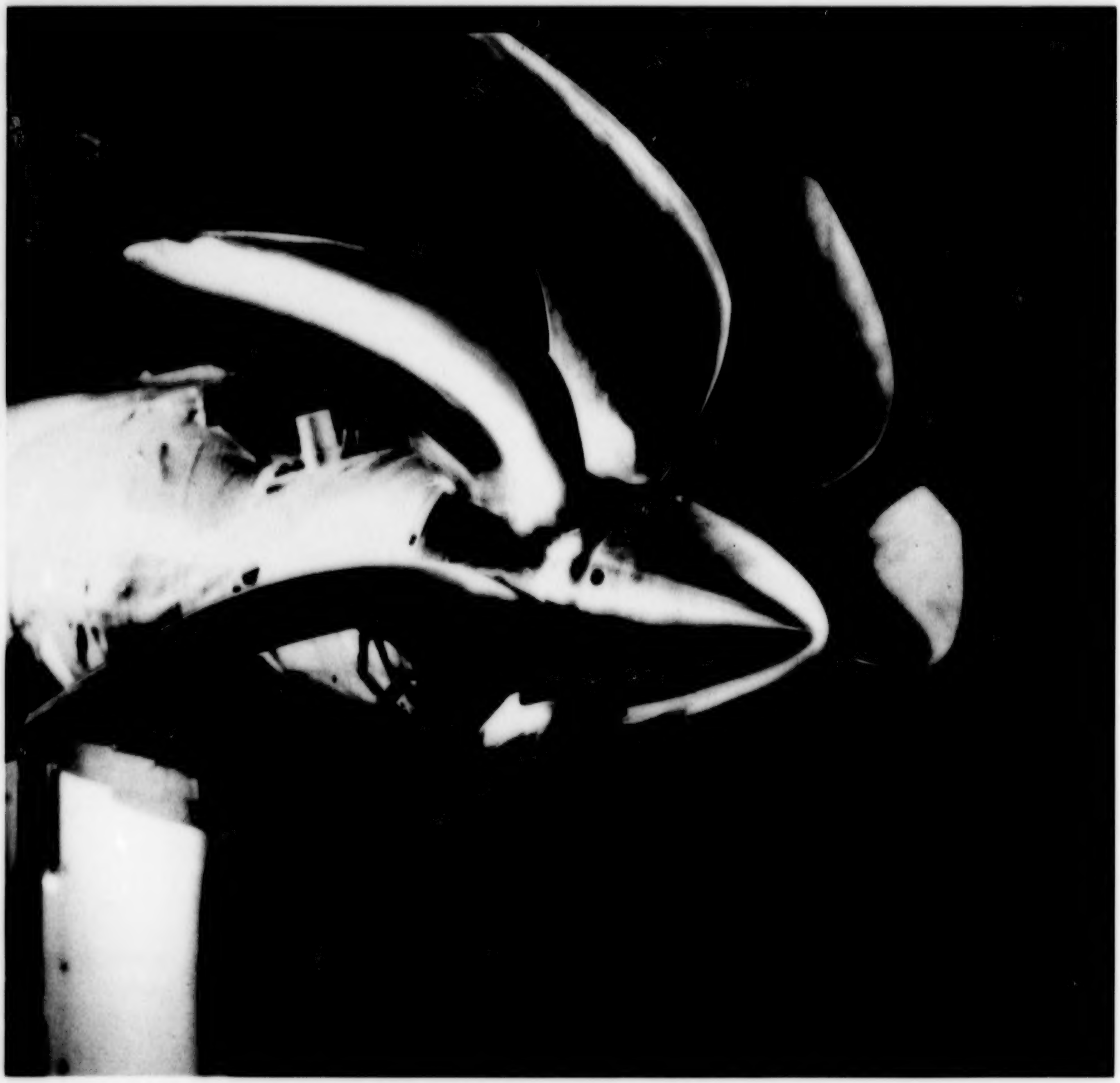


Figure 7.—Model of SR-3.

Several years later a more reasonably sized counterrotating model program was started, and models were designed and tested by both Hamilton Standard and General Electric. Between 1976 and 1978 propfan research was a small effort with minimal funding. Defending and promoting it was a time-consuming task for the few engineers assigned to the research, who had to spend a great deal of time preparing documentation, traveling around the country gathering technical advice from industry and other NASA centers, and debating a whole series of objections brought up by advisory committees and industry.

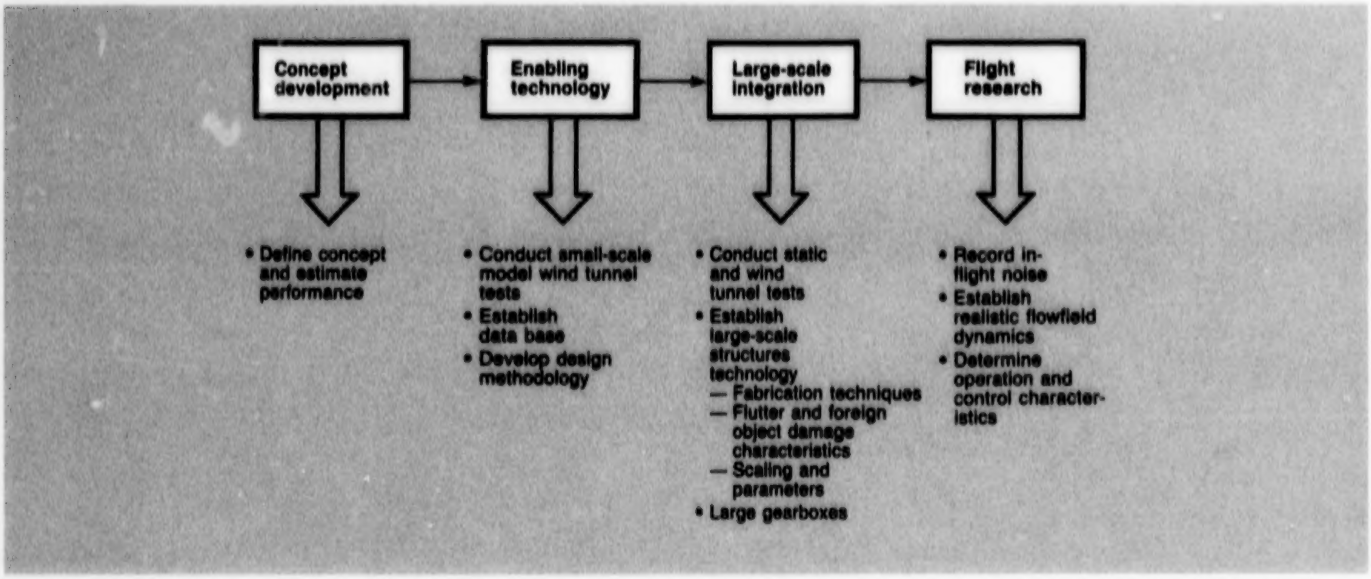

Concept development
Enabling technology
Large-scale integration
Flight research
• Define concept and estimate performance
• Conduct small-scale model wind tunnel tests
• Establish data base
• Develop design methodology
• Conduct static and wind tunnel tests
• Establish large-scale structures technology
— Fabrication techniques
— Flutter and foreign object damage characteristics
— Scaling and parameters
• Large gearboxes
• Record in-flight noise
• Establish realistic flowfield dynamics
• Determine operation and control characteristics

Figure 8.—Structure of Advanced Turboprop aircraft.

Their efforts were rewarded in 1978 when NASA formally began the Advanced Turboprop (ATP) Project with overall project management at Lewis. The objective was to establish both single- and counterrotating propfan technology for Mach 0.65 to 0.85 applications. Project goals were to show fuel and direct operating cost savings over comparable turbofans and aircraft interior noise (or vibration) similar to that of turbofans in order to meet Federal Aviation Regulations on noise (FAR–36) and to establish by the late 1980's the technology readiness of a safe and reliable propulsion system.

In cooperation with NASA Headquarters, project managers at Lewis structured the ATP Project by separating the work into distinct parts, each with its own goals. Technical issues would first be resolved through wind tunnel testing of small-scale models before the more costly large-scale ground and flight testing. Figure 8 shows the use of this philosophy in planning the project.

The project managers called the time before the project officially began, when NASA and Hamilton Standard performed design work and small-scale propeller tests, concept development. A small group of researchers demonstrated then that efficiency was maintained at the higher Mach numbers. This was the key evidence that helped to justify the rest of the ATP Project. They called the first years of the ATP Project, 1978 to 1980, enabling technology. During this time NASA and its contractors performed additional small-scale tests and developed design codes to establish the feasibility of the propfan. They established a fundamental data base of propfan technology that consisted of design, analysis, and testing techniques. The effort called large-scale integration began in 1981. The knowledge gained in the enabling technology work was used to design, fabricate, and ground test a single-rotating, large-scale (9-foot diameter) propfan and gearboxes in the 6000-shaft-horsepower size. Flight research, which started in 1987, involved flight-testing a large-scale propfan to provide scaling comparisons with model tunnel data and to validate computer analyses. When these tests are completed, they will be followed by an analysis effort comparing results to design intent.

Enabling Technology

In planning the work to be done in each period the project managers had to think in terms of a system that could be integrated with an entire aircraft, as shown in figure 9. This systems approach would require expertise in several research areas at Lewis, as well as at Langley, Ames, and Dryden.

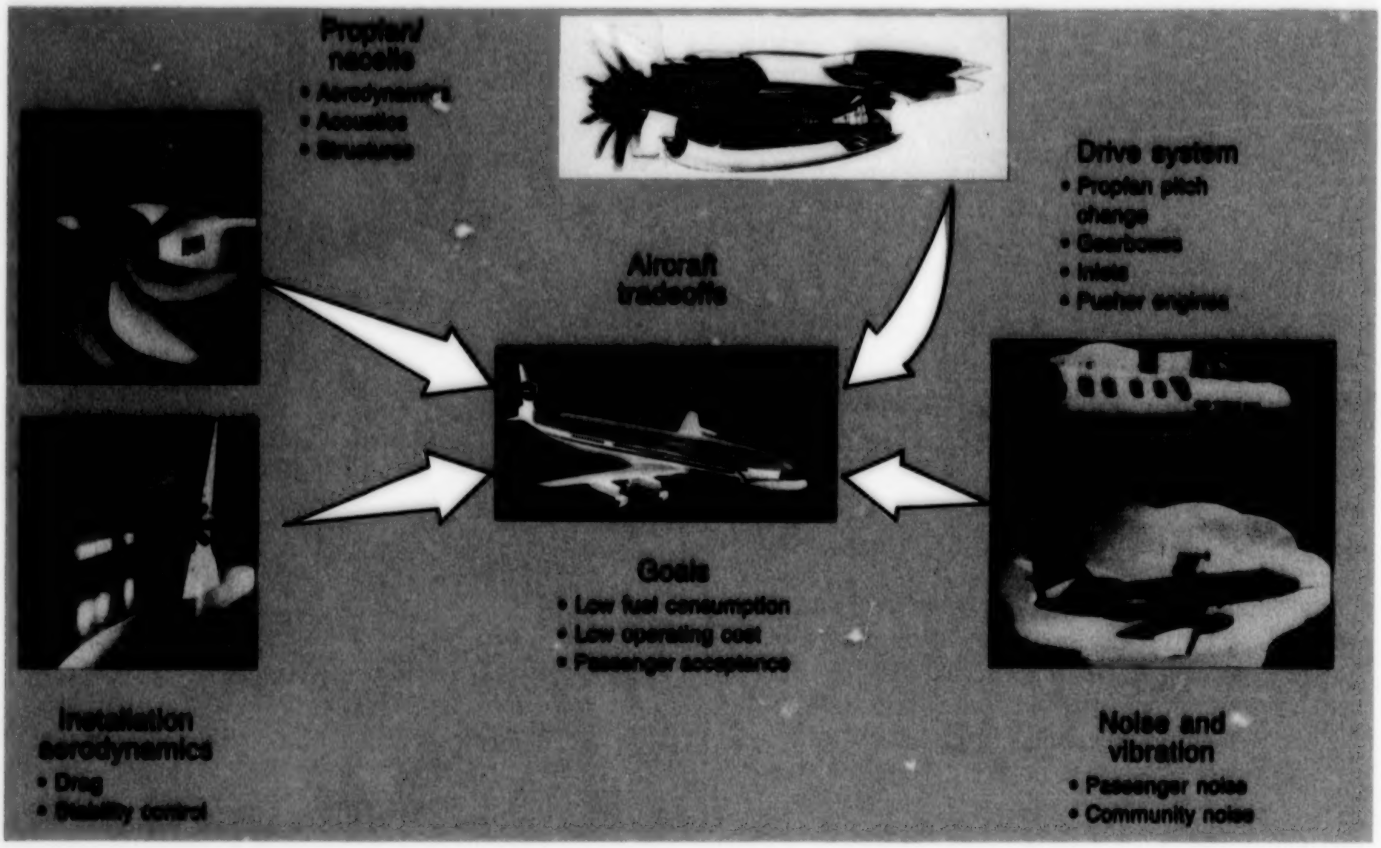

Propfan/ nacelle
• Aerodynamics
• Acoustics
• Structures
Drive system
• Propfan pitch change
• Gearboxes
• Inlets
• Pusher engines
Aircraft tradeoffs
Goals
• Low fuel consumption
• Low operating cost
• Passenger acceptance
Installation aerodynamics
• Drag
• Stability control
Noise and vibration
• Passenger noise
• Community noise

Figure 9.—Elements needed to develop advanced turboprop aircraft.

One major concern was aircraft interior noise. Knowing that acoustic tunnel testing at higher Mach numbers was not a mature technology and that adequate source noise analysis codes did not yet exist, acoustics experts were recommending flight verification of the data. Under Lewis direction Dryden took responsibility for the proposed model-source-noise flight testing and Langley for much of the aircraft interior environment analysis. Also because matching the comfort and quiet of turbofans would probably require reducing noise by as much as 50 to 55 decibels, Langley researchers needed to study the problem of attenuating aircraft interior noise without increasing fuselage weight to the point of completely canceling all the turboprop's fuel efficiency gain.

Installing the turboprop on a wing could reduce the efficiency of both the wing and the turboprop, severely limiting any efficiency gain. Model tests were planned to study these installation effects in the Ames and Langley wind tunnels.

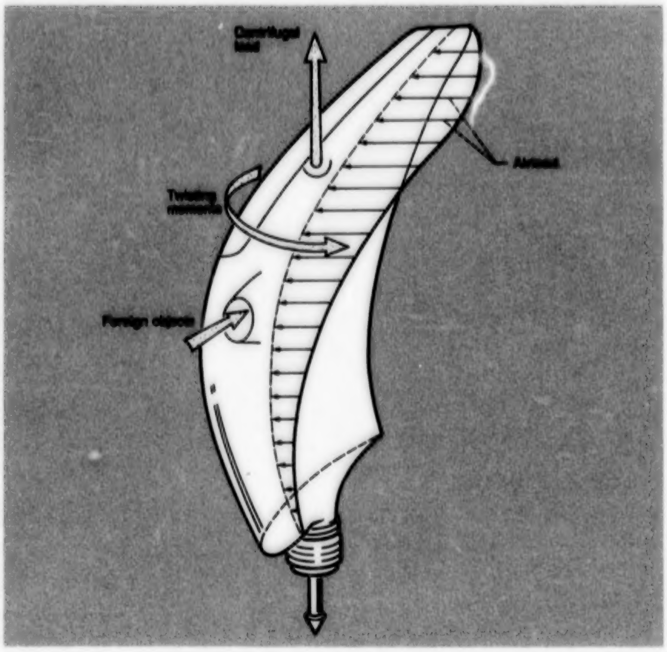


Figure 10.—Blade structural environment.

The structural design of the propfan blades combined almost every complexity previously experienced with the structures of conventional propellers, helicopter rotors, and fan blades. The blades had to withstand foreign object damage (erosion, stones, ice, birds), to be free of classical high-speed and static stall flutter and forced vibrations, and to withstand the steady air and centrifugal loads (fig. 10). The thin, swept blades have high stresses in the root area due to the bending and twisting forces caused by the airload and by the centrifugal load from the overhung mass. Also as the rotational speed increases, the blades tend to untwist. This affects their aerodynamic shape at cruise. To solve these structural problems, Lewis engineers planned a combination of scale-model tests and code development by both NASA and industry.

Because of the blade number and power levels neither the drive system's gearbox nor its blade pitch-change mechanism could be of conventional design. Lewis along with several major engine companies planned to develop the gearbox and pitch-change technology needed for a complete turboprop propulsion system.

Design Code Development

Since the cessation of propeller research and the beginning of the computer age had been almost simultaneous, the computational improvements that normally accompany the use of computers had not been made in propeller design. Results of tunnel tests performed in the 1950's were not incorporated, and few propeller design codes existed. Those that did exist were two-dimensional codes, suitable for the straight, untwisted propellers of the 1950's, but hardly adequate for the highly loaded, complex geometries of the propfan. The Lewis and Hamilton Standard engineers' approach was to develop new design codes by combining design and analysis techniques for conventional propellers, helicopter rotors, swept wings, and turbofans.

One of the first propfan performance codes, the advanced lifting-line analysis, was developed from a technique of the 1950's and was used to predict thrust, power, and efficiency. This analysis represented each blade with a curved lifting line at the quarter chord point and included an effect for an axisymmetric nacelle. A flow grid representing a single-rotating propfan with a nacelle is shown in figure 11. Lifting-line methods are still the best way of computing overall propfan efficiency, but they do not provide much detail since they predict only the radial load distribution. Predicting the chordwise distribution, which would allow computation of the detailed blade load, requires three-dimensional methods.

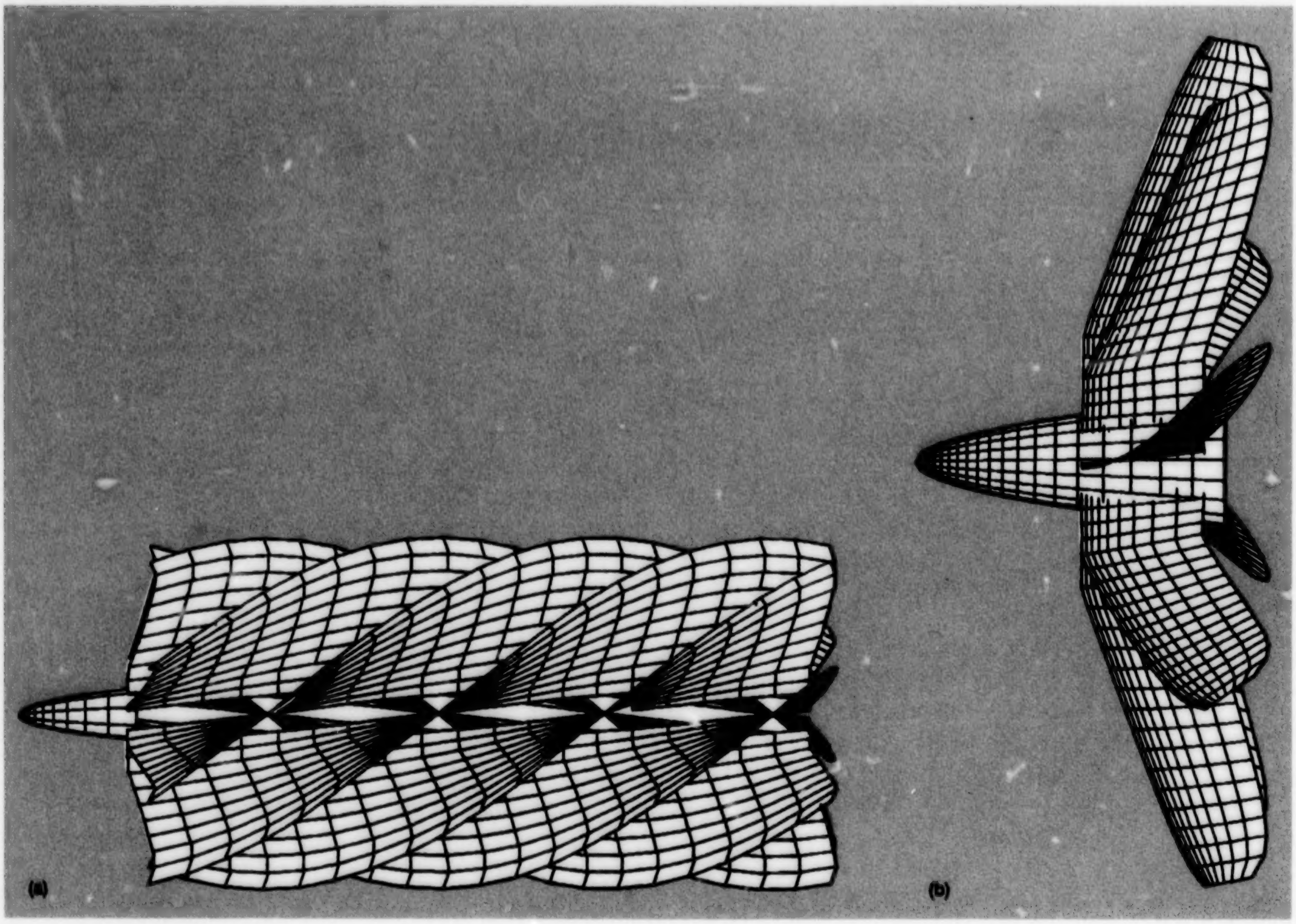
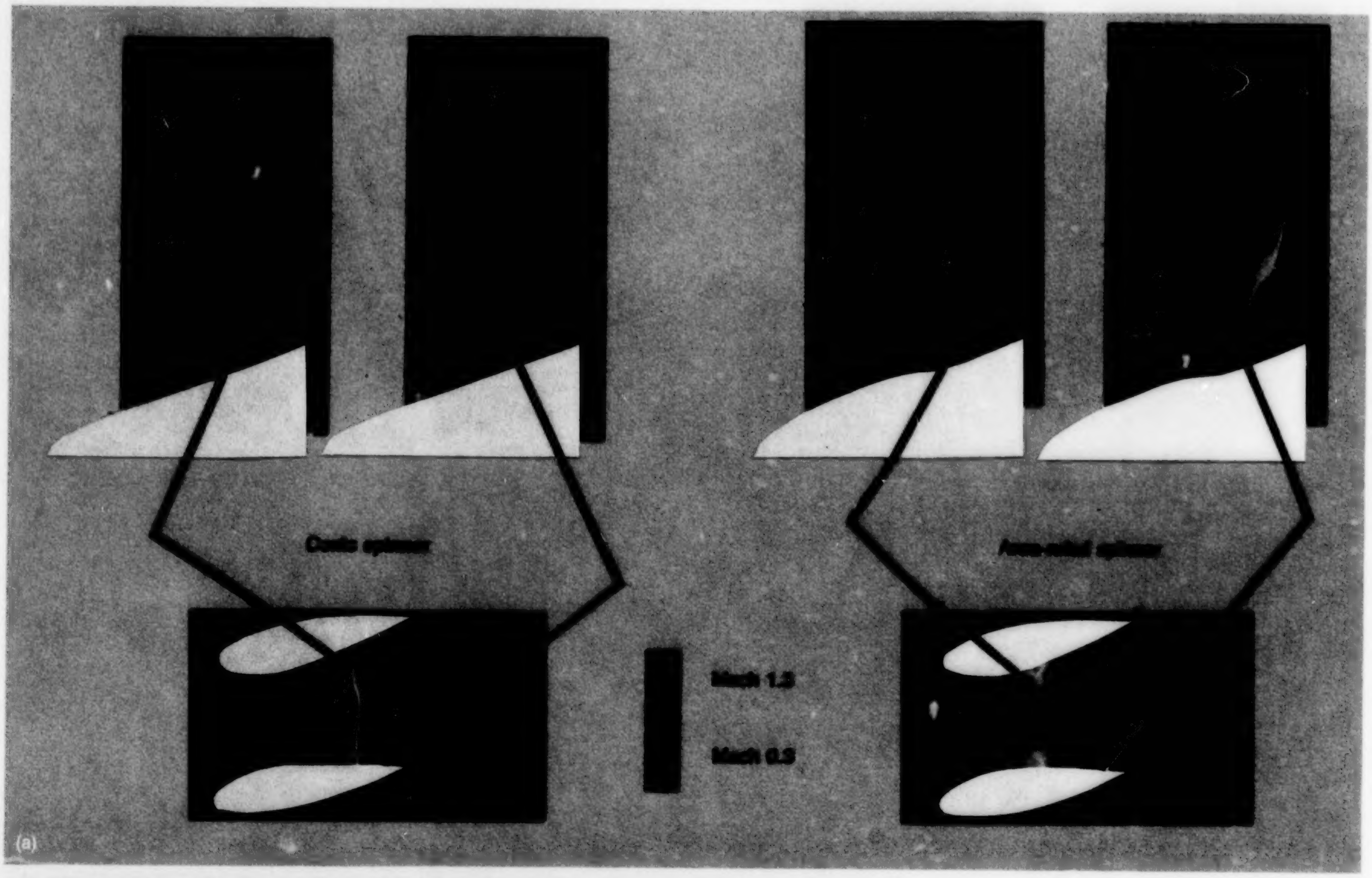


Figure 11.—Representations of new design codes. (a) Lifting line. (b) Lifting surface.

Using their expertise in computational fluid dynamics, NASA Ames researchers developed a finite difference method to provide a three-dimensional, lifting-surface representation of the blade by including the effects of thickness, sweep, and twist (fig. 11). With finite difference methods flow velocities, pressure, and density are calculated everywhere in the flowfield about the blade and on its surface. Therefore they effectively predict radial and chordwise distributions in the same analysis. After the initial development at Ames, Lewis engineers expended considerable effort to turn the code into a practical aerodynamic analysis. Lewis studies using this code gave the first indication of shock waves on the propfan blades in spite of blade sweep and also the first indication of hub choking on some models.

The code developed at Ames and Lewis was the first three-dimensional propeller aerodynamic analysis that used finite difference methods to solve Euler equations. Because of the work done at this time Euler codes are now recognized as powerful design tools and are becoming standard in propeller design. Both the lifting-line and Euler (lifting surface) aerodynamic analysis methods are widely used today. Usually, because they take less computer time, lifting-line analysis methods are used in the preliminary design, and Euler methods, because of their greater detail, are used for analyzing the final design. Examples of Euler three-dimensional analysis for unsteady flow are shown in figure 12. The flow visualization in figure 12(a) shows a local Mach number reduction due to the area-ruled spinner. Figure 12(b) shows the variation in blade pressure contours as a result of angle of attack. Figure 13 shows a generalized flowfield computed for a counterrotating system by Euler analysis. Work is continuing to provide more detail of counterrotating flowfields and to include unsteady three-dimensional effects.


(a)
Conic spinner
Area-ruled spinner
Mach 1.3
Mach 0.3

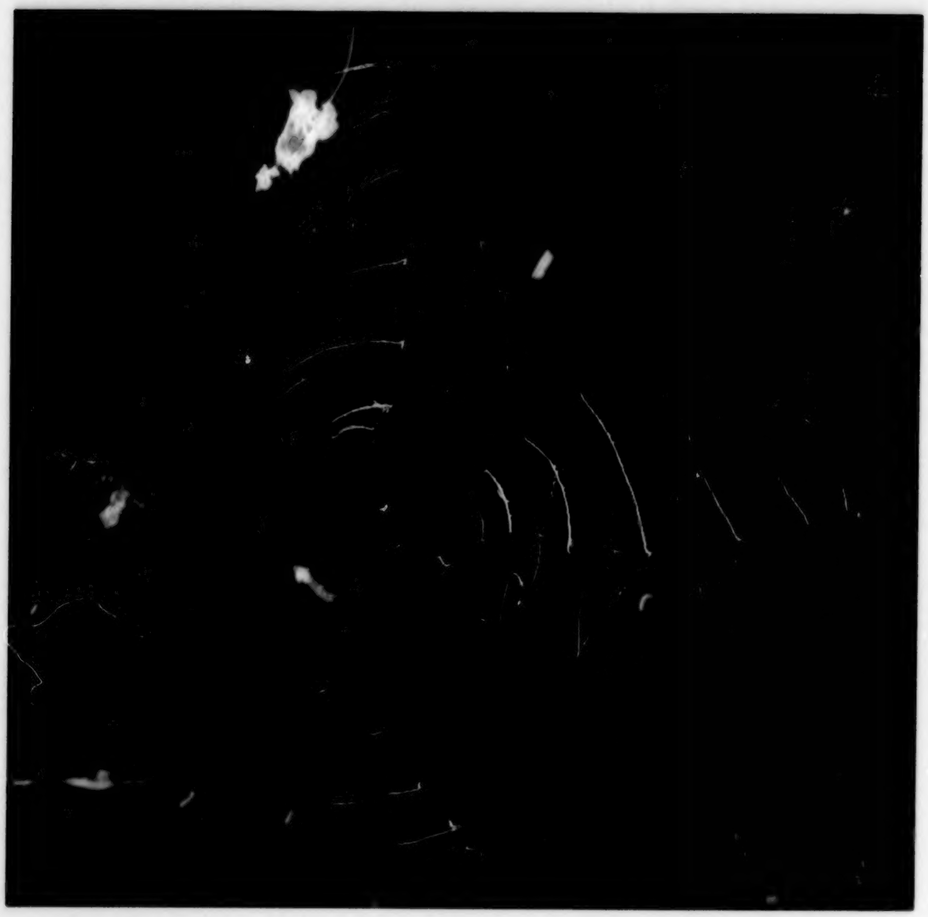


Figure 12.—Examples of Euler three-dimensional analyses for unsteady flow. (a) Local hub effect of spinner contouring on throat Mach number between adjacent blades (SR-1M model at Mach 0.8). (b) Instantaneous chordwise pressures with 4° angle of attack (SR-3 model at Mach 0.8).

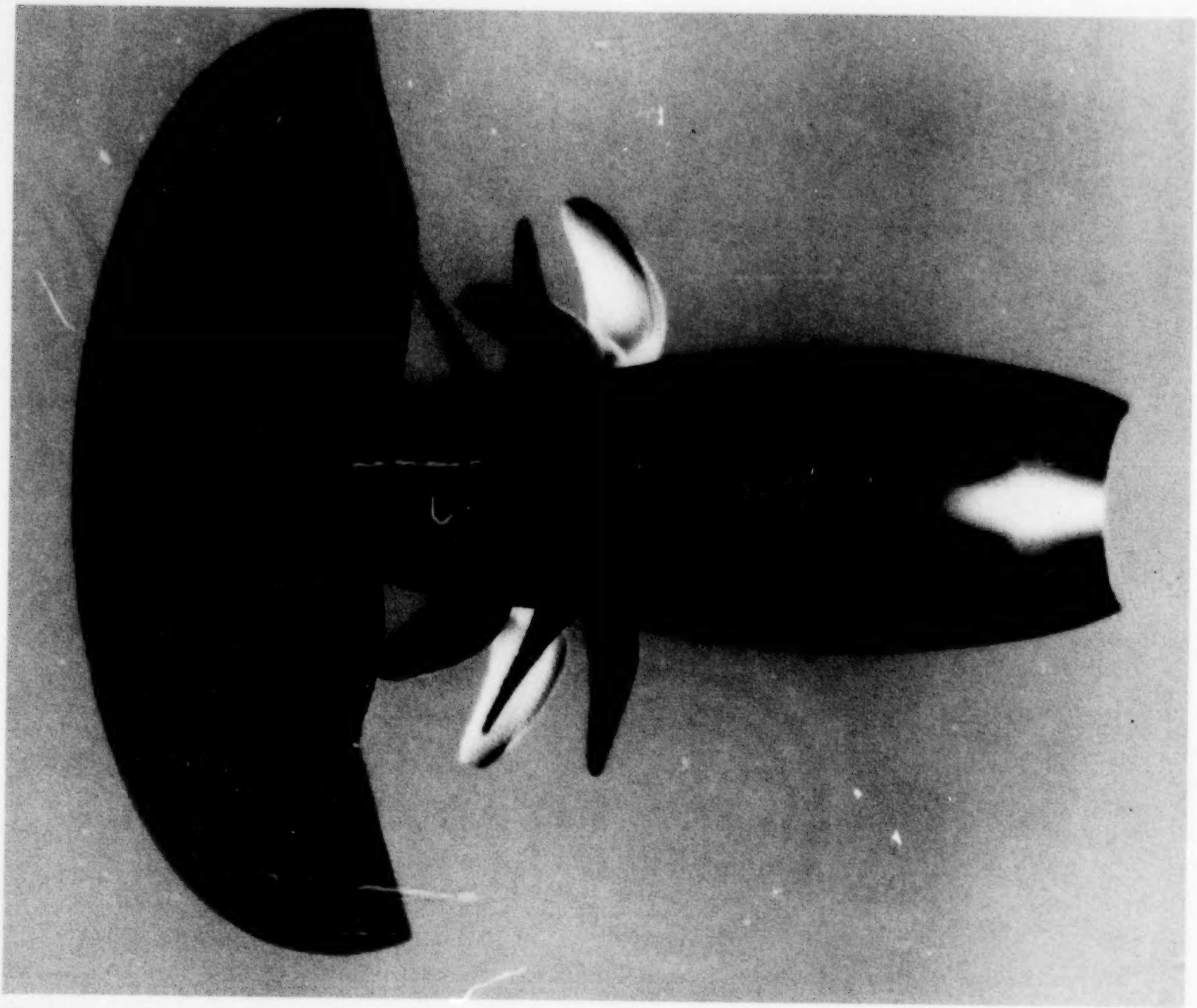


Figure 13.—Generalized flowfield for counterrotating blade rows and nacelle.

Acoustic analysis codes underwent similar modifications. One method used for acoustic predictions involves computing the noise generated by a series of spanwise strips on a blade (fig. 14). The noise signals from these compact sources are summed to give the overall noise generated by the blade. This method is only approximate but is being improved by considering loading effects in the calculations. Hamilton Standard and Langley developed noncompact source methods, which compute sound at any point in the far field by taking into account the pressure disturbance along the chord line of a blade operating in a uniform flowfield. In the future unsteady incidence angles and pressure fields and the unsteady interaction pressures present with counterrotating rows will also be included in these codes.

In performing the blade aeromechanical design the structural designers faced the same task as the other disciplines—adding sweep effects to codes that were based on two-dimensional analysis. Engineers had used beam methods to estimate blade natural frequencies, mode shapes, and other inherent structural characteristics of conventional straight propellers. But because of the propfan's sweep and low aspect ratio they turned to finite element methods. Although finite element analysis was already three dimensional for straight turbofan blades, it had to be modified further to account for nonlinear centrifugal loading, caused by the relatively large deflections of the swept blades. The example mode shapes in figure 15 show the highly nonlinear character of swept propfan blades.

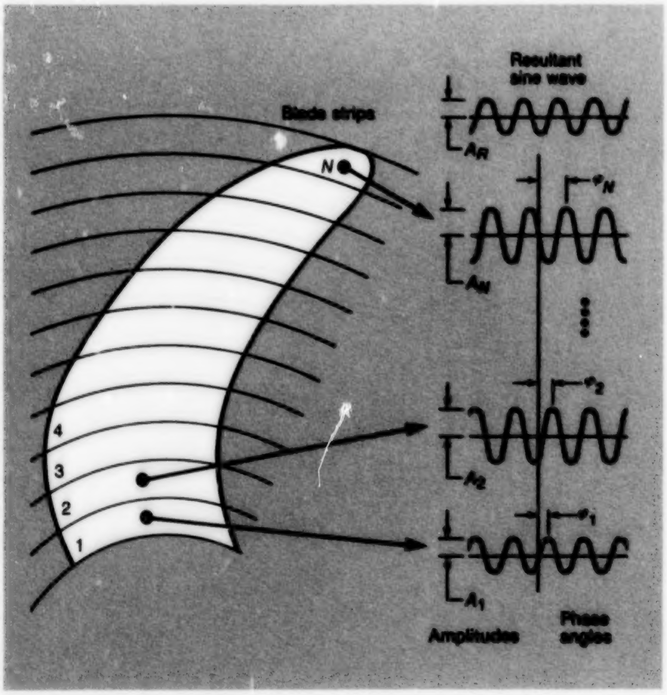


Figure 14.—Strip method of acoustic analysis.

Some concerns that must be addressed in the blade aeromechanical design are forced excitation, stall flutter, and classical flutter (fig. 16). Forced excitations occur over the entire flight envelope and are caused by unsteady, unsymmetrical airflows produced by gusts, upwash from the wing, and airframe-induced flowfield distortions. Forced excitations peak during low-speed climb and high-speed cruise conditions. Flutter is an oscillatory motion of a structure in an airstream where the driving aerodynamic forces are the result of the body motion itself. Stall flutter occurs primarily at low speed and results from separated flow on the blade surface. Classical flutter, a particular concern with propfans, happens at high speeds, beyond Mach 0.6. It involves no separated flow. Another form of vibration, stall buffet, is occasionally found on propellers delivering high power at low forward velocities. It is caused by stalled airflow on the blade itself driving the airfoil, much like forced vibration.

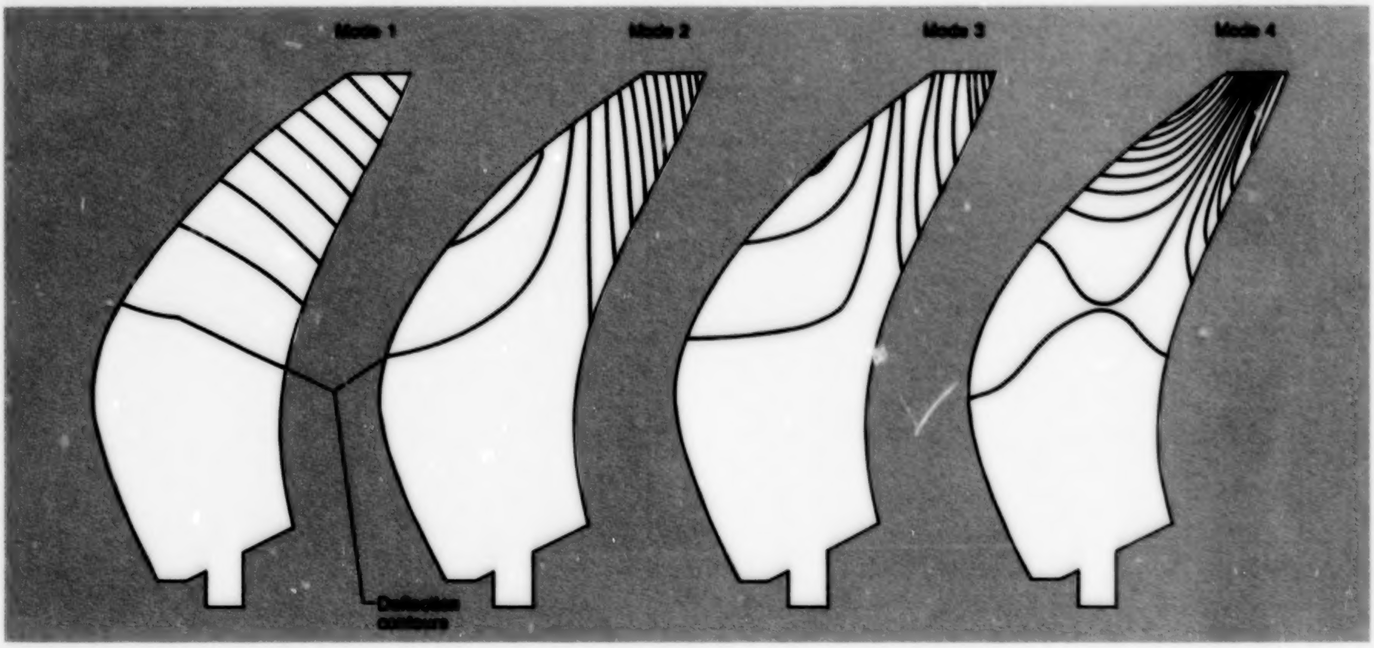


Figure 15.—Mode shapes predicted by finite element methods.

To develop the codes for propfan blade response, techniques found in reports on swept-wing flutter were combined with flutter analysis techniques that had been developed for turbofan blades and straight propeller blades. To determine the stability boundary, sweep effects were incorporated in the structural analysis, and cascade effects were included in the two-dimensional unsteady aerodynamics. Recent improvements to these codes have included adding the effects of three-dimensional transonic and supersonic unsteady aerodynamic and blade row interactions for flutter predictions in counterrotating systems.

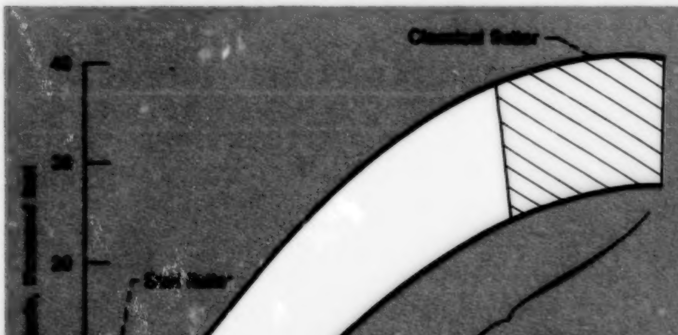


Figure 16.—Blade aeromechanical concerns.

Code Verification

Design codes were continually being modified to predict the performance, acoustics, and structural response of these high-speed, highly loaded swept propfan blades. To verify a new code, researchers compared its output with results of previous, more basic analytical procedures as well as with the results of scale-model tests.

The first model propfan tests were performed by Hamilton Standard under Lewis contract from 1976 to 1978. Although they established that the predicted performance was attainable and verified the benefit of sweep in improving performance and reducing noise, they also showed the desirability of testing model propfans in Lewis wind tunnels.

While Hamilton Standard was testing the first four propfan models, Lewis began to develop their own propfan testing capabilities. An air-turbine-driven rig was converted for testing 2-foot-diameter propfan models and mounted in the Lewis 8- by 6-foot transonic wind tunnel (fig. 17). Also in 1984 the tunnel's 9- by 15-foot low-speed leg was modified by installing acoustic liners in the walls, ceiling, and floor to make it an anechoic tunnel.

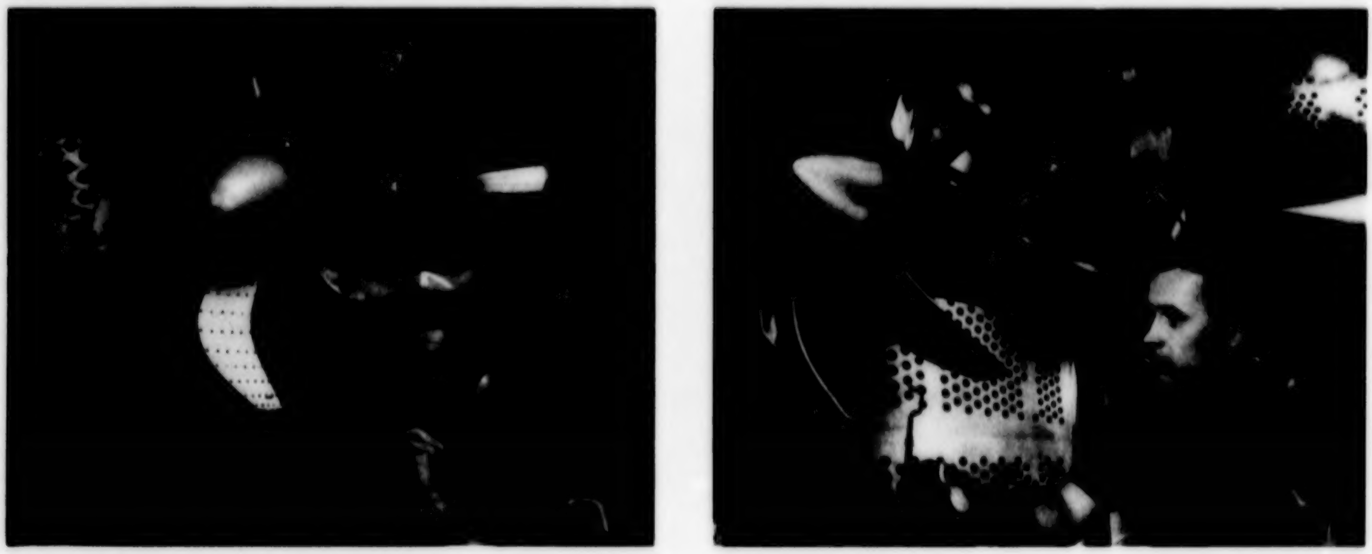


Figure 17.—Propfan models installed in Lewis transonic wind tunnel.

Another major achievement of this early period was the development of a laser velocimeter (LV) system for nonintrusively measuring the flow velocity around propeller blades (fig. 18). This had previously been done with instrumentation such as pressure rakes that altered the flow characteristics just by their presence. The LV system could be operated from outside the tunnel, and its light beams did not interfere with the flow around the model. It could even be used to measure flow conditions between the blades, where pressure instrumentation could not be installed (fig. 19).

The four propfan models were tested with the new Lewis test rig mounted in the transonic wind tunnel to verify the aerodynamic and acoustic performance previously shown in the Hamilton Standard tests. The Lewis data agreed with the Hamilton Standard data and confirmed that the 30° sweep of the SR–1 yielded 77 percent efficiency at Mach 0.8—about a 1-percentage-point improvement over the straight-blade SR–2 efficiency of 75.8 percent. Redistributing the spanwise loading on the SR–1M improved its performance to 78 percent. The SR–3 model with its 45° tip sweep yielded the highest propulsive efficiency, 78.7 percent—an improvement of approximately 3 percentage points over the straight-blade SR–2.

Figure 18.—Laser velocimeter installed in Lewis transonic wind tunnel.

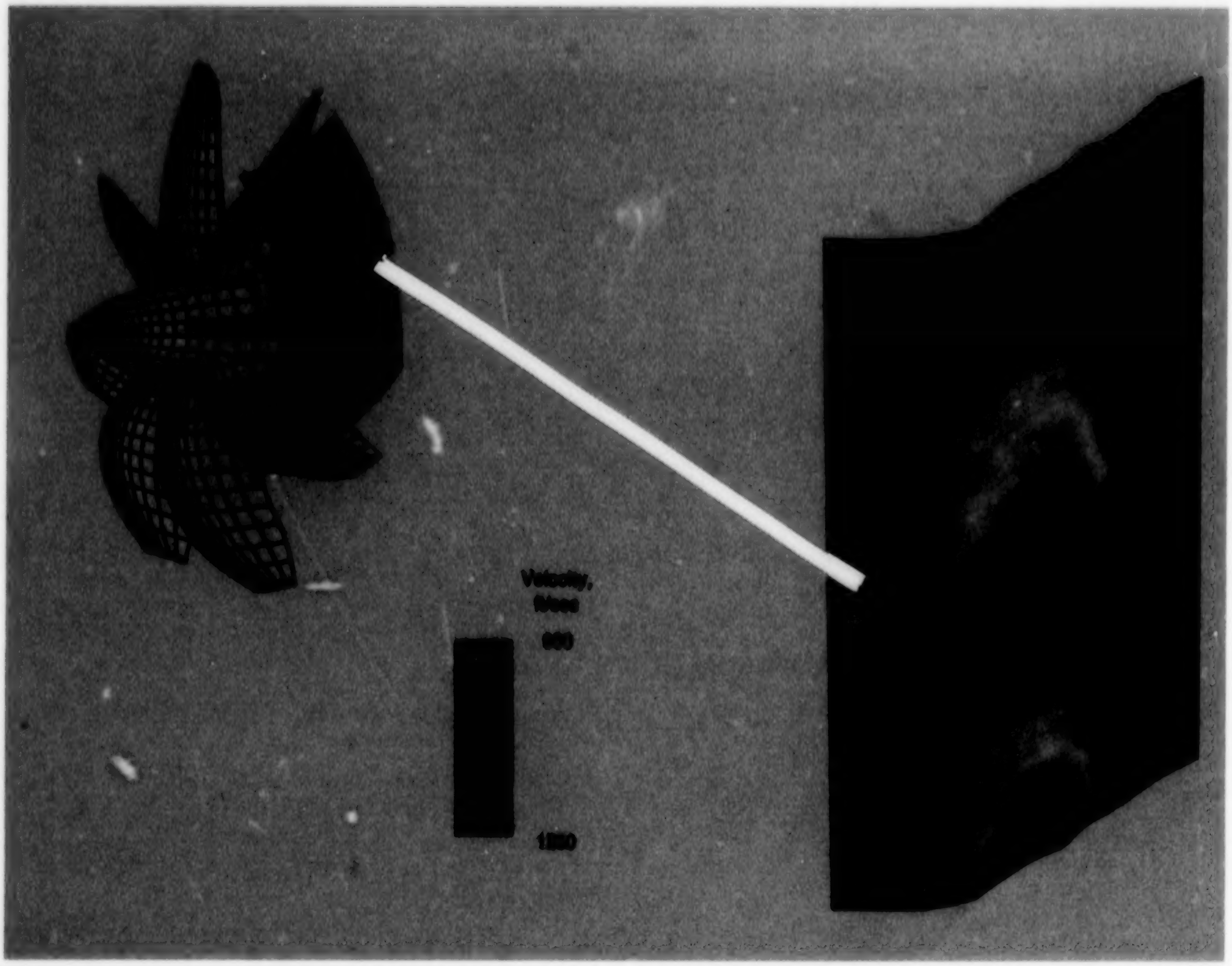


Figure 19.—SR-3 interblade relative velocity at Mach 0.8 measured by laser velocimeter.

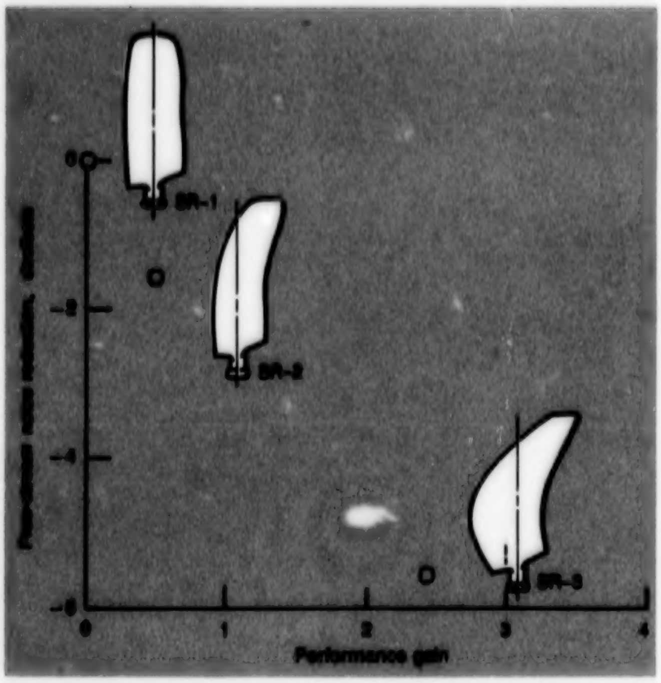
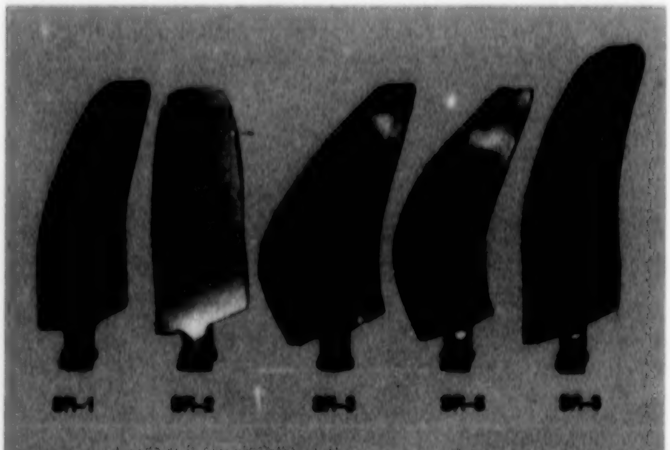


Figure 20.—Noise characteristics of propeller models at Mach 0.8 and 37.5 shaft horsepower per diameter squared.



	SR–1	SR–2	SR–3	SR–5	SR–6
Tip sweep, degrees	30	0	45	60	40
Number of blades	8	8	8	10	10
Power loading	37.5	37.5	37.5	26	30
Tip speed, feet/second	800	800	800	600	700

Figure 21.—Propfan test model blades.

Improvements in noise reduction paralleled those in performance (fig. 20). The straight-blade SR–2 was the noisiest, with the SR–1M only slightly quieter. The third model, the SR–3, which had a sweep distribution tailored for noise reduction, showed the lowest noise level—about 5 decibels less than the SR–2 at Mach 0.8 cruise. Lewis then began testing other models in the transonic wind tunnel: the SR–5, a 10-blade model designed by Hamilton Standard with 60° sweep, the maximum they believed a metal blade could have without excessive stresses; and the SR–6, a 10-blade model with 40° sweep designed by Lewis. The SR–6 was NASA's first in-house aerodynamic propfan design. The blades, design parameters, and assemblies are shown in figures 21 and 22.

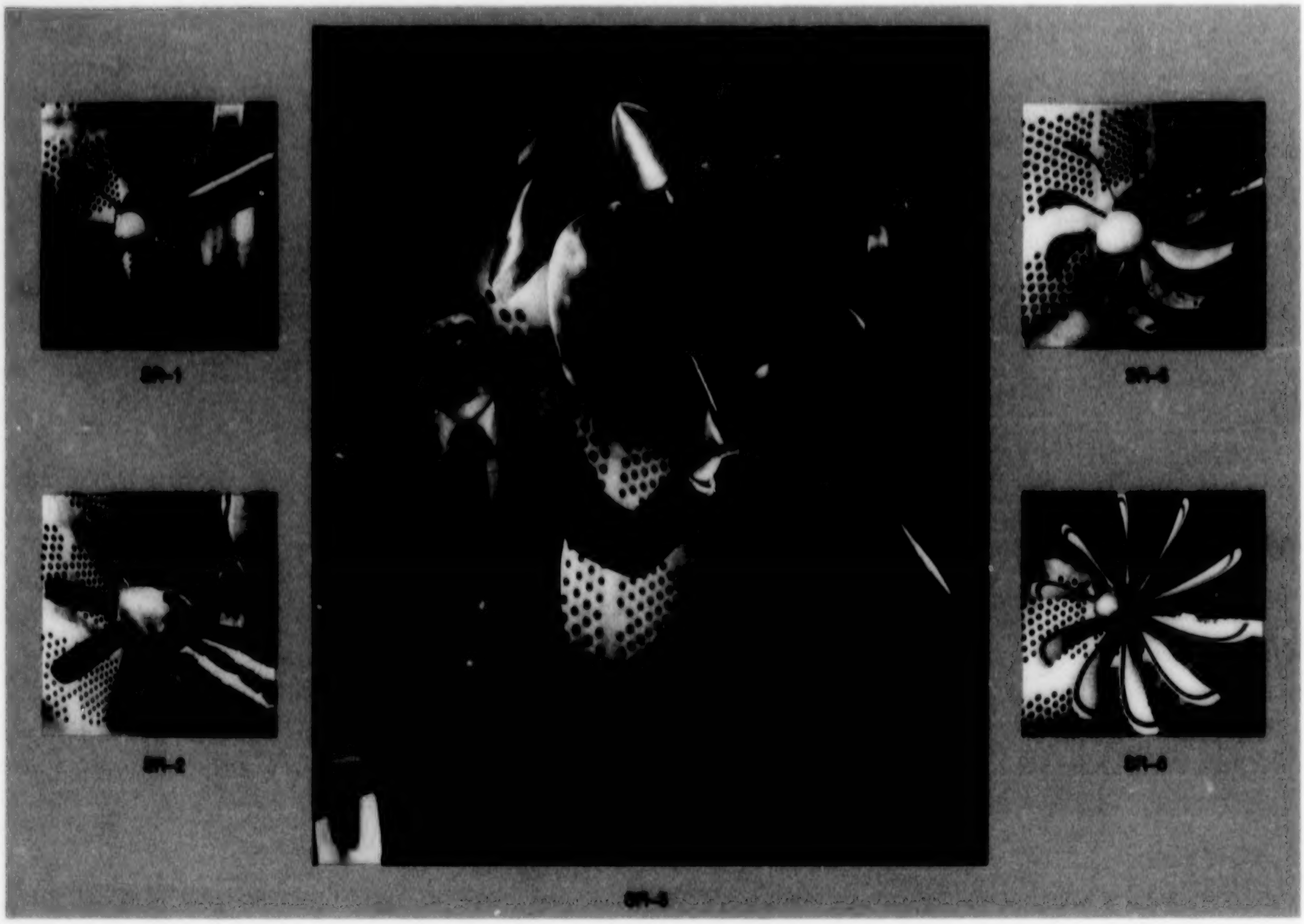


Figure 22.—Propfan test models installed in Lewis transonic wind tunnel.

In an effort to reduce noise even further the Lewis engineers reduced the loading and tip speed of the SR–5 and SR–6. Wind tunnel tests showed that the SR–6 model was about equal in noise to the SR–3 and was about 79 percent efficient at Mach 0.8. Its performance fell off rapidly with speed, probably owing to choking in the blade root (fig. 23).

During performance testing in the Lewis transonic wind tunnel the SR–5 propeller encountered high-speed, classical flutter and thus could not achieve its design point. Although this was viewed as a problem at the time, this test provided valuable data for verifying improved structural analysis methods.

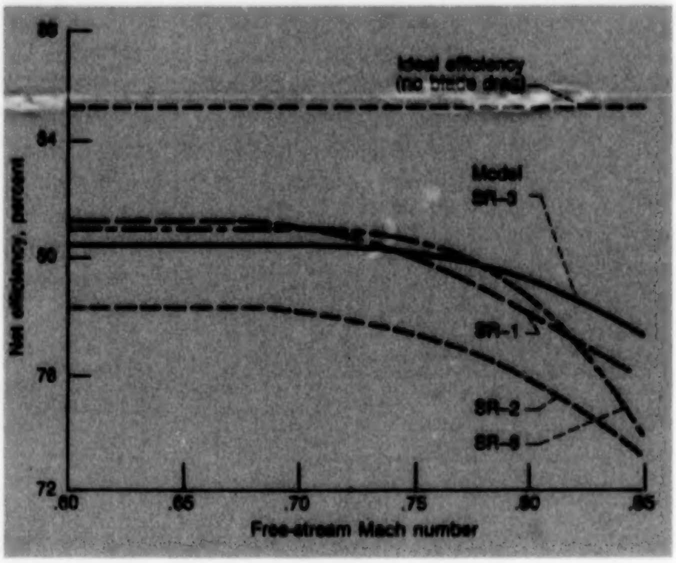


Figure 23.—Measured efficiency of propfan test models. Advance ratio, 3.06; power coefficient, 1.7.

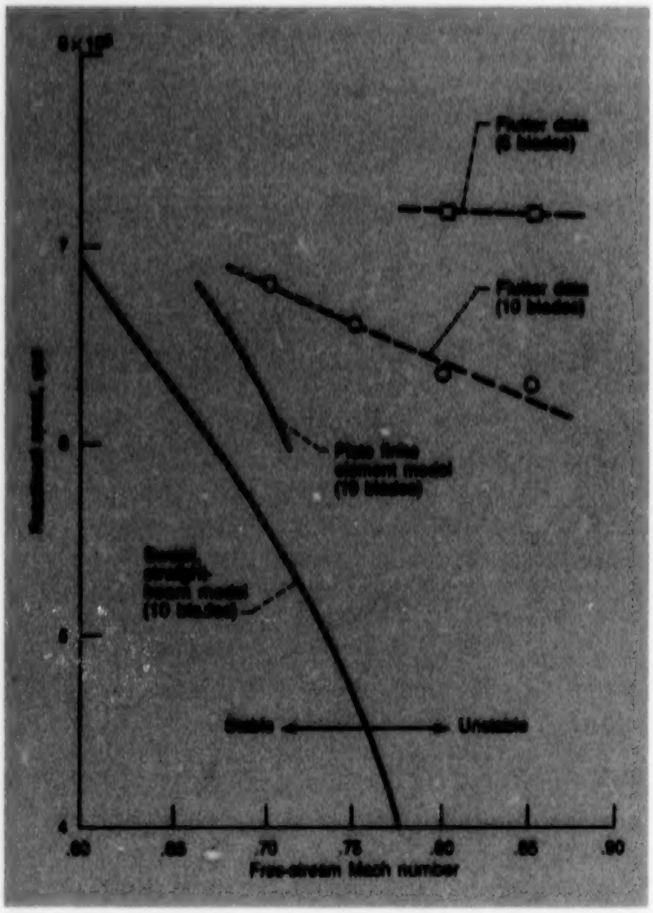


Figure 24.—Predicted and measured SR–5 flutter boundaries.

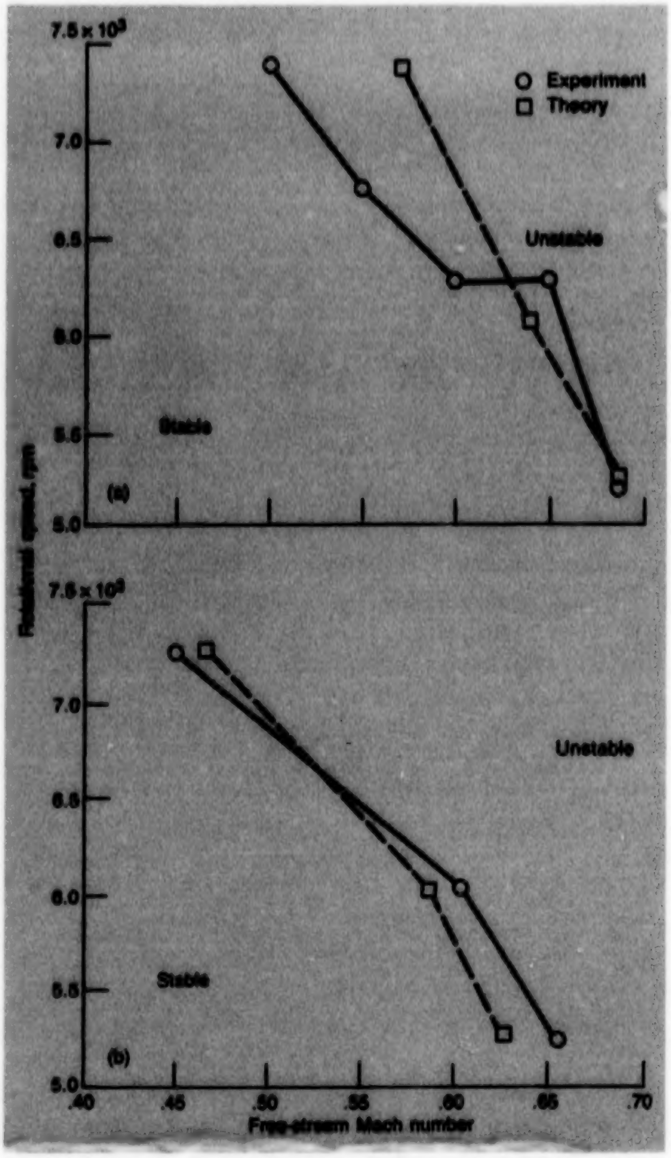


Figure 25.—Predicted and measured SR–3CX2 flutter boundaries. (a) Four blades. (b) Eight blades.

Since the SR–5 developed instability above Mach 0.7 for the 10-blade configuration and above Mach 0.8 for 5 blades, a two-dimensional subsonic cascade effect was included in the structural code. A predicted flutter boundary was computed using a straight-beam blade model and a flat-plate finite element model. As figure 24 shows, the finite element model better represented the data but still needed work.

The unsteady aerodynamic effects were replaced with a three-dimensional subsonic code, and the blade structure was represented by a cambered finite element model. To expand the data base on classical flutter of swept propellers, two composite SR–3 blades were designed with different ply orientation to change their torsional stiffness. The SR–3C was stiffer and predicted to be stable; the less stiff SR–3CX2 was predicted to flutter. Tests in the Lewis transonic wind tunnel confirmed these predictions. However, as shown in figure 25, the four-blade configuration of the SR–3CX2 did not match the theory at all free-stream conditions. This implied that the theory was overcorrecting for the decrease in the aerodynamic cascade effect with four blades.

Solving the Aircraft Interior Noise Problem

From the model tunnel tests Lewis engineers expected to be able to design a propfan with an airborne noise level of about 145 decibels. The design would be similar to the SR-3, with the loading distributed radially to reduce noise generated at the tip. Because the aircraft interior goal was 90 decibels, the sidewall attenuation would have to be about 55 decibels. Therefore existing sidewalls with conventional acoustic treatment, which can achieve a noise reduction of about 30 decibels, were inadequate, and new methods to attenuate an additional 25 decibels had to be developed.

Noise from the propeller and the engine traveling through the air and striking the cabin wall was not the only consideration, as shown in figure 26. Structural excitations resulting from the gearbox and engine, the propeller, and the propeller wake striking the nacelle and the wing can be transmitted to the airframe and penetrate the fuselage. For an acceptable aircraft interior environment these excitations would have to be dealt with in addition to the airborne noise.

JetStar Project

Knowing that the acoustic data from wind tunnels needed to be verified, engineers at Dryden worked to provide in-flight acoustic data. A NASA-owned JetStar was modified for this purpose in 1979. A 2-foot-diameter propfan was mounted on top of the JetStar fuselage (fig. 27). The propfan was driven with an air turbine powered by engine bleed air. Flush microphones were mounted on the fuselage near the model and at other locations on the wing. A boom was mounted on the aircraft nose so that the flight conditions and the angle of attack could be accurately recorded.

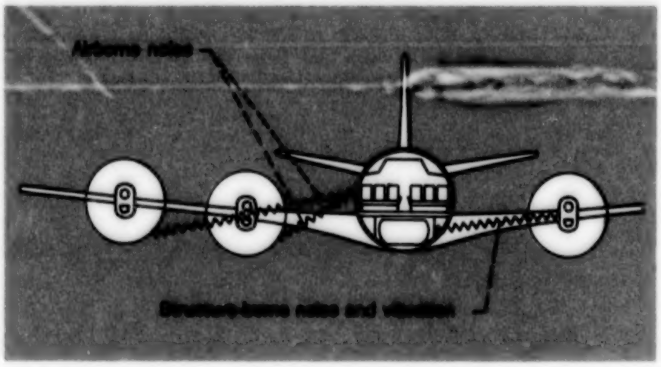


Figure 26.—Sources of cabin noise and vibration.

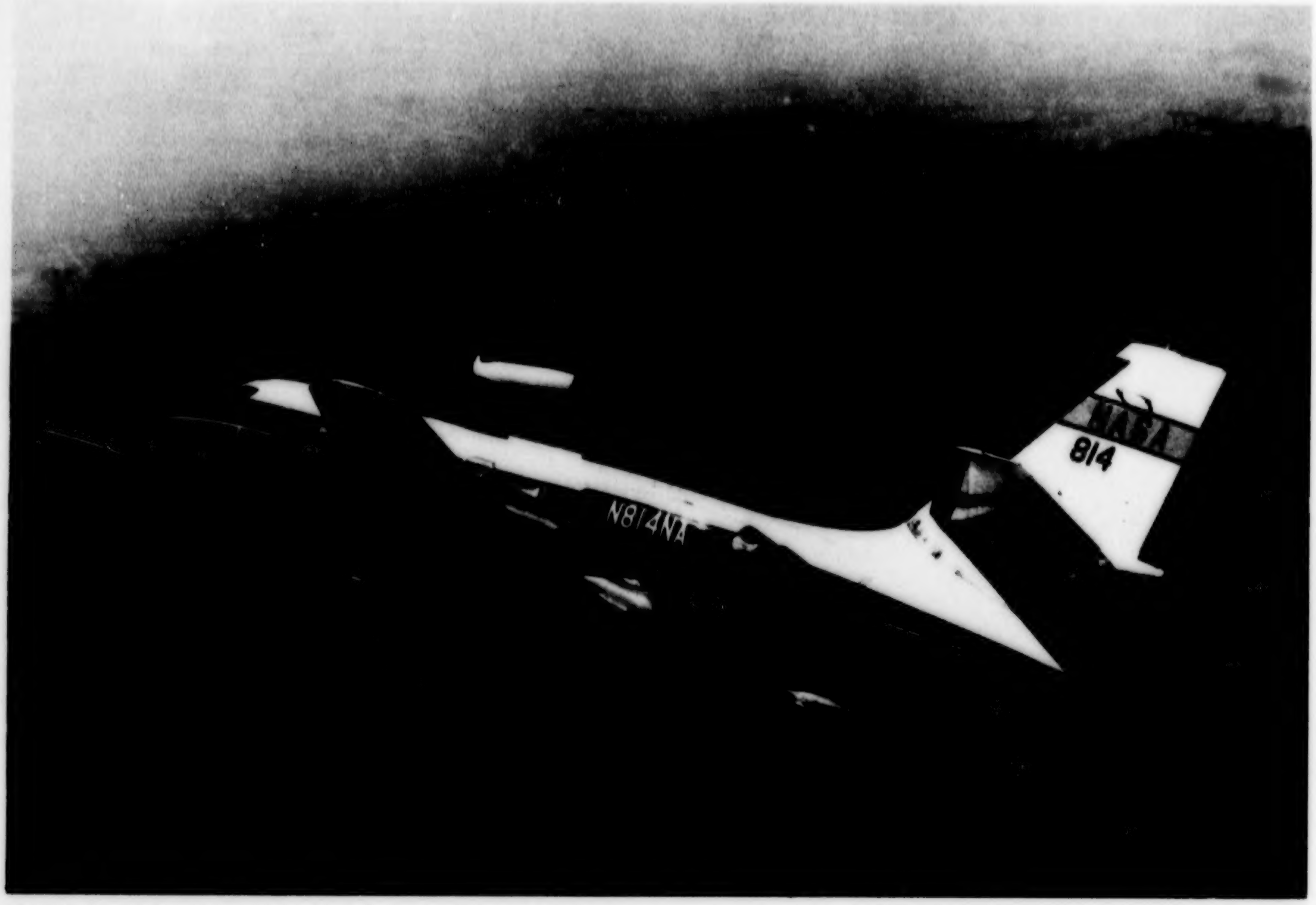

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Figure 27.—Modified JetStar with model propfan installed.

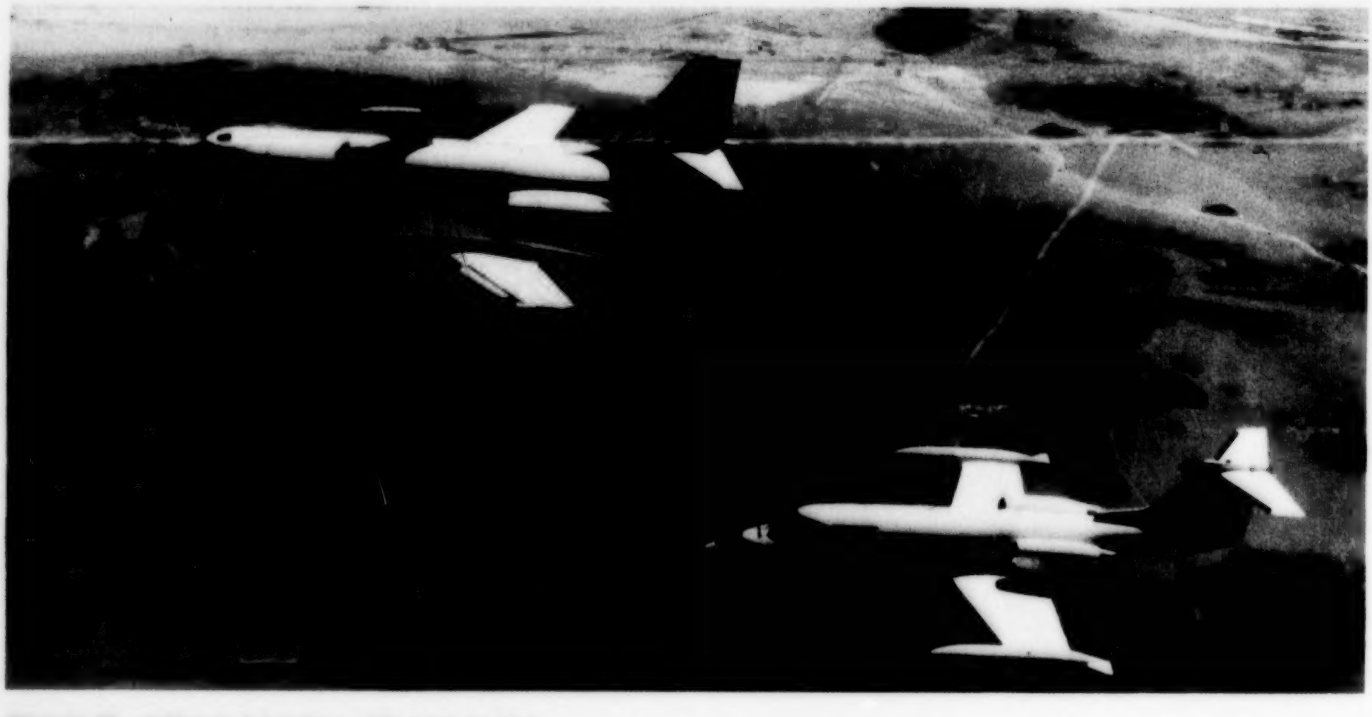


Figure 28.—JetStar in formation with NASA Learjet.

Flight tests were made at Dryden to Mach 0.8 with both four- and eight-blade SR–3 models, an eight-blade SR–2 model, and two- and eight-blade SR–6 models. Further flight tests with two- and eight-blade SR–3 models were made during formation flights using a Lewis Learjet (fig. 28) with wingtip- and nose-mounted microphones to measure far-field noise. Analysis of the noise generated by the SR–3 propfan (fig. 29) demonstrated that noise propagates spherically (fig. 30). The measured levels were slightly below predicted (fig. 31) and tended to support the acoustic wave theory rather than the shock wave theory (fig. 32). These data provided a realistic idea of the far-field noise that would be generated by the propfan in flight. Engineers could thus better determine the steps needed to reduce the noise within the cabin.

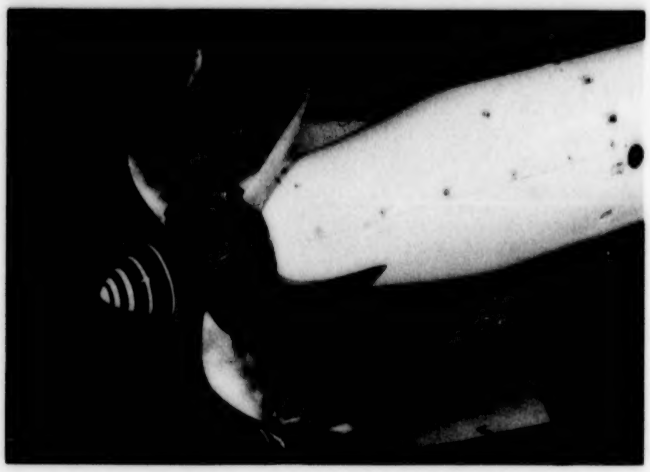


Figure 29.—SR–3 propfan model installed on JetStar pylon.

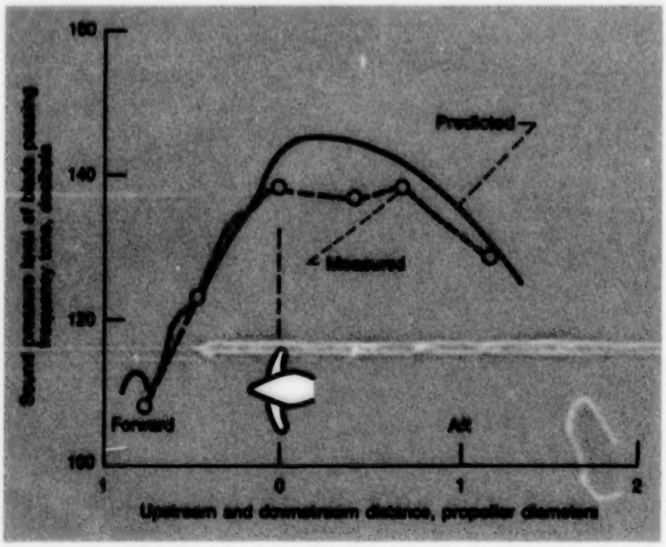


Figure 31.—Predicted and measured propfan noise during Mach 0.8 cruise at 30,000 feet.

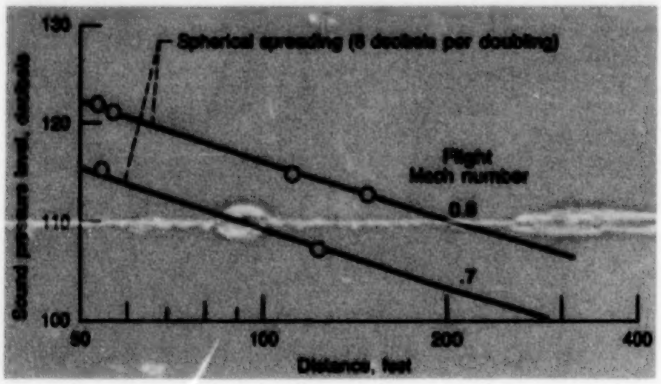


Figure 30.—Spherical propagation of propfan noise.

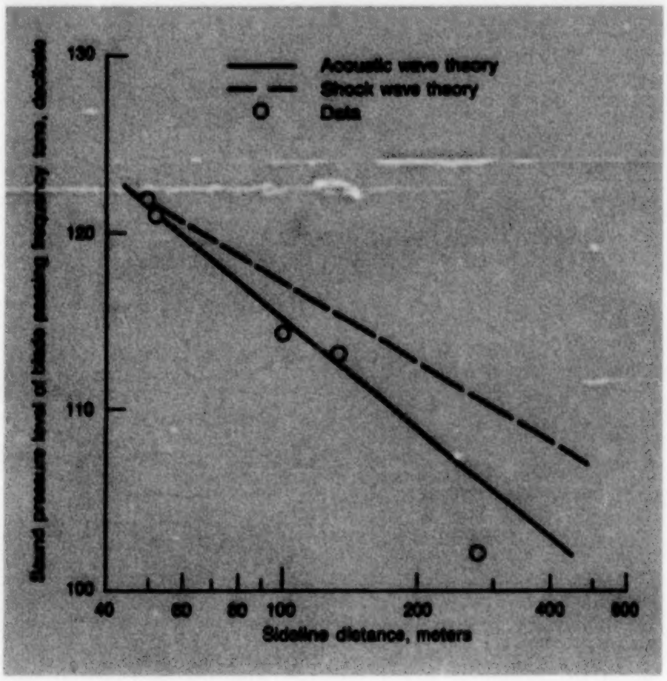


Figure 32.—Acoustic and shock wave theory compared with results of flight test at Mach 0.8 and 30,000 feet.

Figure 33.—Twin Otter prepared for structure-borne noise test.

Acoustic Technology Tests

Preliminary tests using a Twin Otter (fig. 33) with a fuselage-wrap noise barrier designed to reduce airborne noise transmission showed that substantial levels of acoustic disturbances are carried into the cabin through the airplane structure. These results verified the need to attenuate structure-borne as well as airborne noises. The data also showed the engineers that they needed a variety of ways for reducing the noise level in the aircraft interior in order to attenuate both structure and airborne noise. One of the most promising approaches they assessed was to design a fuselage that would provide maximum noise attenuation. But it was also one of the most complicated since any additional weight could also reduce fuel efficiency. In 1982 Lockheed-California, using the fuselage section and facility shown in figure 34, completed tests on five acoustic fuselage treatments. They found that the interior noise reduction goal of 55 decibels could be achieved with acceptable weight penalties while retaining a conventional aluminum fuselage load-carrying structure (fig. 35).

In addition to advanced acoustic treatments engineers studied other methods of attenuating noise. A comprehensive structure-borne noise program that is still continuing started in 1985 using a modified OV–10 Bronco (fig. 36). This program involves determining the acoustic effects of blade rotation relative to the fuselage (up inboard versus down inboard) and the effects of angle of attack, as well as separating airborne and structure-borne vibrations to determine the extent of each. In addition, the program includes experiments with methods of attenuating noise, such as active noise suppression, which involves using cabin speakers to broadcast canceling sound waves, and syncrophasing, which involves controlling the propellers so that one blade on each propeller is vertical at the same time on each revolution.

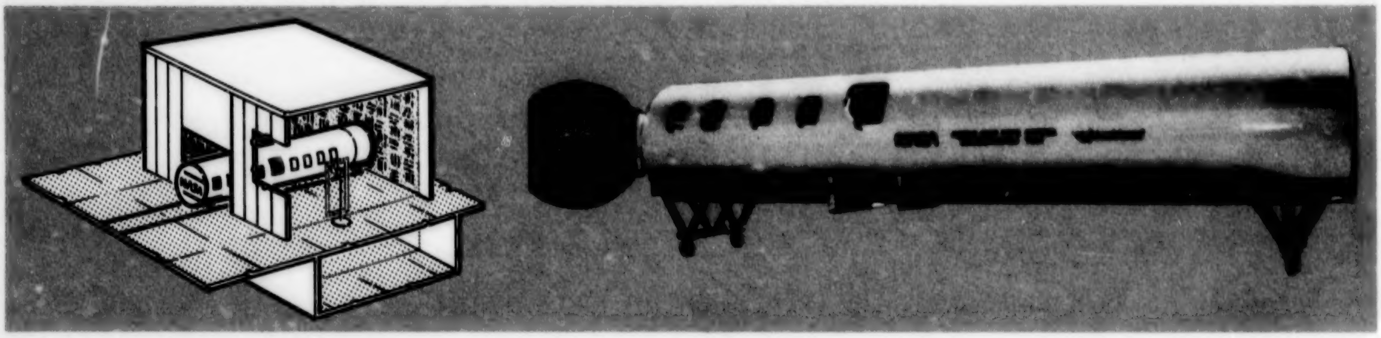


Figure 34.—Test facility used for demonstrating high-performance sidewall noise control.

Results show that changing the rotating direction from up inboard to down inboard reduces noise by several decibels and that active suppression with speakers can be very effective at certain cabin locations. Structure-borne noise was again shown to be an important part of the interior noise, indicating that it must be considered in aircraft design.

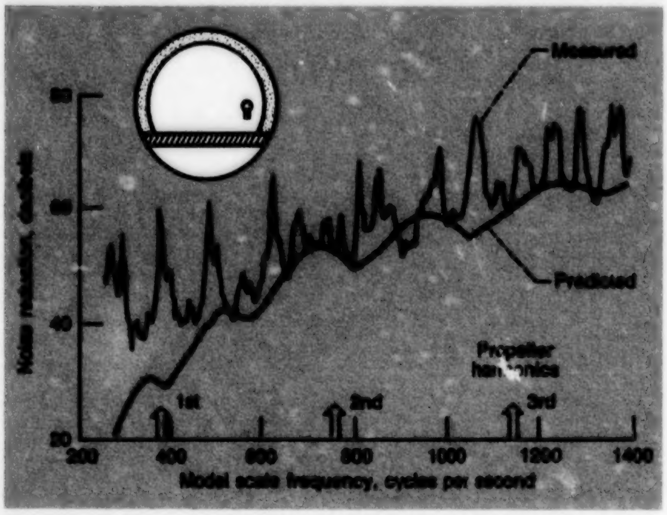


Figure 35.—Noise reduction provided by high-performance sidewall design.

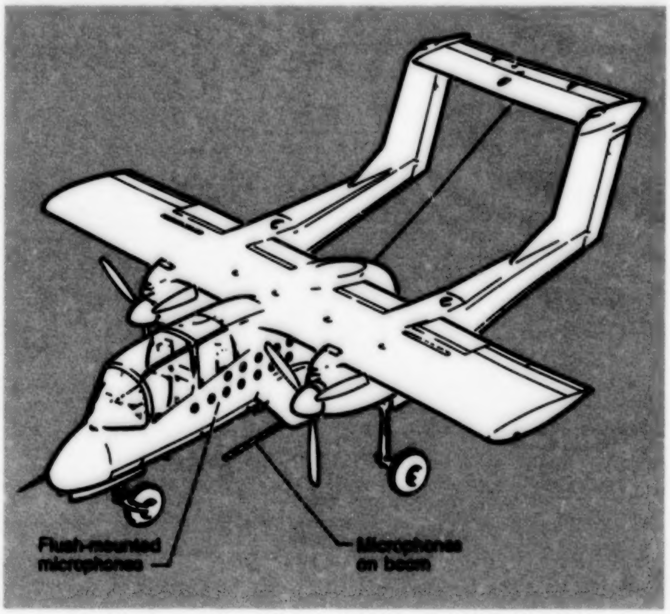


Figure 36.—Microphones mounted on OV–10 Bronco.

Counterrotation Tests

In 1983, looking toward the possibility of testing counterrotating propfans, researchers flew a Fairey Gannet aircraft, which has conventional counterrotating propellers. Lewis and Hamilton Standard measured blade interaction stresses in flight at a maximum speed of 200 knots (approximately Mach 0.3). The Fairey Gannet has two 12.3-foot-diameter, four-blade propellers that can be shut off independently. The stress levels on its aft blades during counterrotation testing were about 25 percent higher than during single-rotation testing. The stresses on the forward blades changed very little. As shown in figure 37 the predicted vibratory stresses agreed fairly well radially with the measured values.

Acoustic tests were performed with the Lewis Learjet in formation (fig. 38). Noise data from both the boom microphones on the Fairey Gannet and the far-field microphones on the Learjet also showed a strong interaction tone from the counterrotating propellers. This type of data gave an early indication of how the single-rotating codes could be extended to counterrotating blade systems.

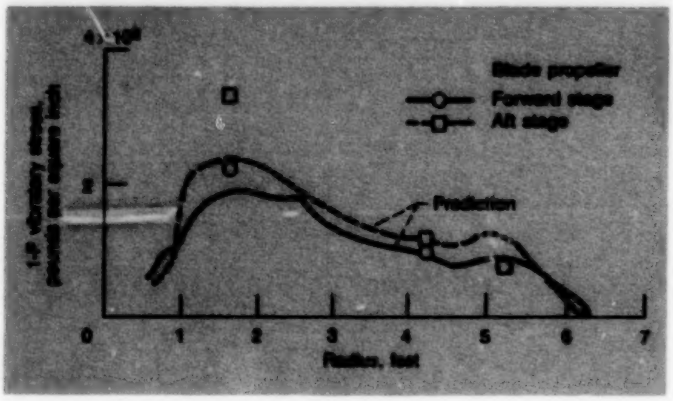


Figure 37.—Vibratory response of large-scale conventional counterrotating propeller on Fairey Gannet.

Figure 38.—Fairey Gannet in formation with NASA Learjet for noise measurement.

Installation Aerodynamics

While researchers at several facilities—among them Hamilton Standard, General Electric, and Boeing—continued to study propfan noise in order to sharpen the accuracy of the analytical prediction techniques, others concentrated on identifying the configuration that was most suitable for an advanced turboprop aircraft. Two basic installations were tested (fig. 39): the wing-mounted tractor and the aft-mounted pusher. The objective of the installation aerodynamic effort was to provide a comprehensive data base to assist industry in selecting a configuration, including whether single- or counterrotation best suited the application. For an effective installation the wing and nacelle had to be integrated to avoid drag penalties and aircraft stability and control problems.

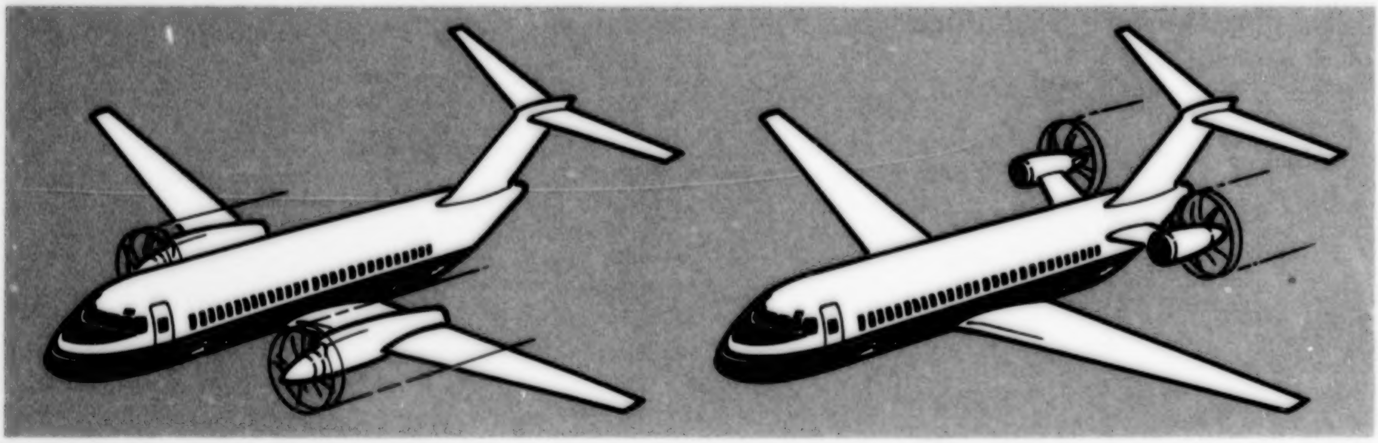


Figure 39.—Advanced turboprop installations.

In order to determine the best possible propfan–nacelle–wing configuration with low installed drag and high slipstream swirl recovery, much work needed to be done. So that they could improve the computer code for analyzing propfan slipstream flow over the wing and the nacelle, researchers needed to understand propfan slipstream behavior and to define the magnitude and source of flow interactions. The first step was taken in 1977 when a McDonnell Douglas propeller slipstream simulator (fig. 40) was used in the Ames 14-foot wind tunnel to study the interaction between slipstream and wing. A slipstream simulator was mounted upstream of a contoured wing and tested to Mach 0.8. Swirl was found to be the dominant factor in both the force and pressure data. At zero swirl the drag penalty over the Mach number range was quite small. At 7° swirl the drag increments increased 5 to 10 counts. This established the importance of determining a wing contour that would have low cruise drag when operating in a high-swirl slipstream.

In 1980 a semispan wing with an under-the-wing nacelle and an SR–2 propfan was tested in the Ames tunnel (fig. 41). The model was tested over a wide range of cruise Mach numbers, aircraft angles of attack, propfan blade angles, and rotational speeds. Results verified the earlier simulator results, showing dramatic increases in drag with no wing or nacelle contouring.

Figure 40.—Propeller slipstream simulator installed in Ames wind tunnel.

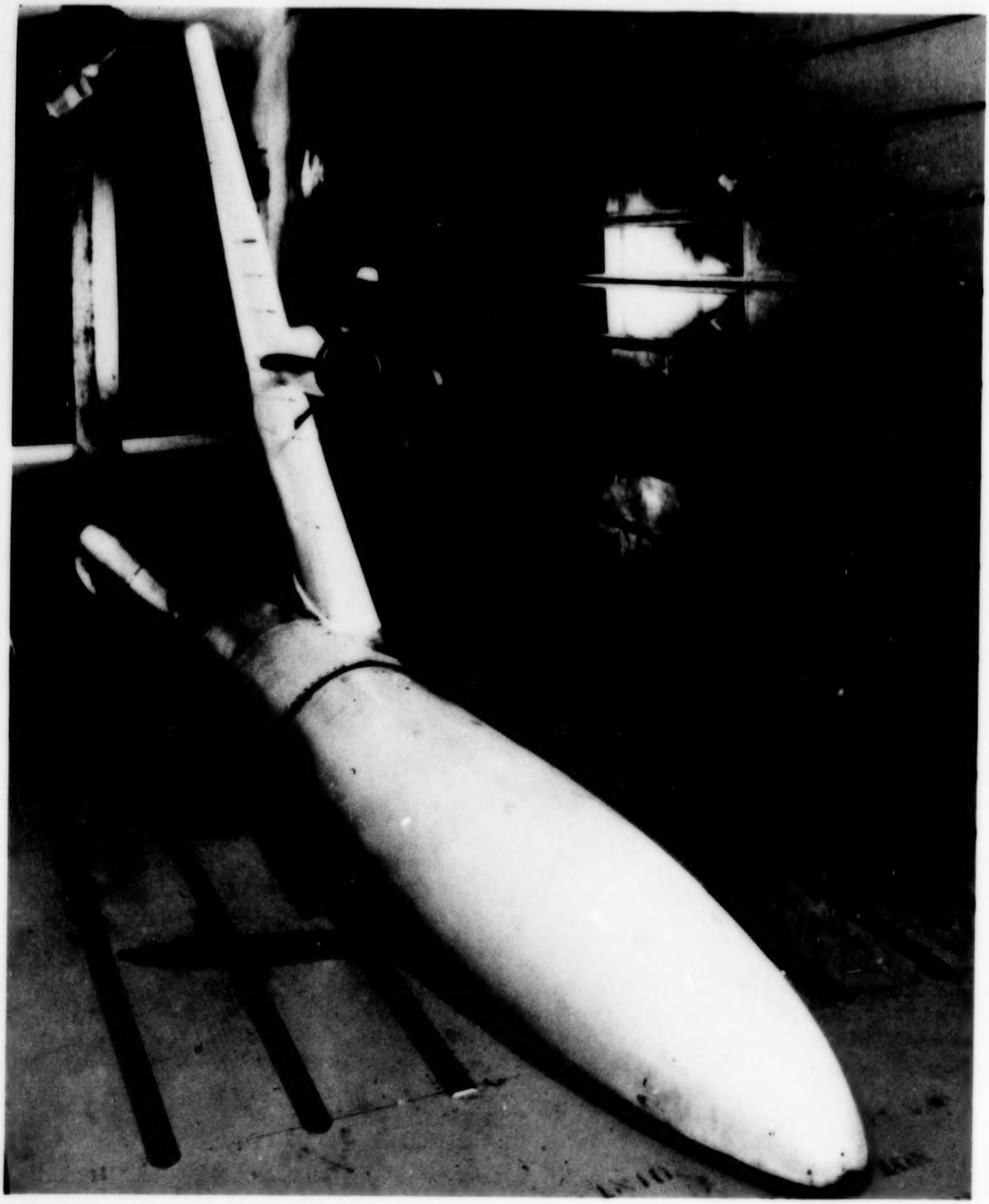


Figure 41.—Semispan wing models installed in Ames wind tunnel.

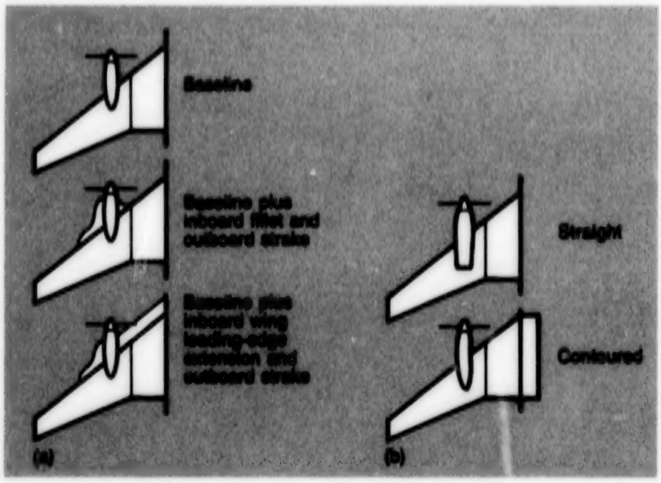

Baseline
Baseline plus inboard fillet and outboard strake
Baseline plus inboard wing leading-edge extension and outboard strake
(a)
Straight
Contoured
(b)

Figure 42.—Nacelle–wing configurations tested in Ames wind tunnel. (a) Under-the-wing nacelle. (b) Over-the-wing nacelle.

Next a series of tests were performed to evaluate the effects of the under-the-wing nacelle with wing leading-edge extensions and a contoured over-the-wing nacelle (fig. 42). The results shown in figures 43 and 44 verify the importance of designing the propfan–nacelle–wing as a system to account for the slipstream swirl.

A follow-on test of the over-the-wing nacelle model, performed in 1983 with the SR–2 in the Ames tunnel, also proved the importance of proper contouring in reducing drag. The wings and nacelles of this model were not matched to the flow conditions, and the leading-edge fairings were designed for a different nacelle contour and wing airfoil. As a result drag was acceptable when the model was unpowered but much higher when the propfan swirl was added. Similar results would occur with the under-the-wing nacelle if it were designed incorrectly.

There was also concern about the effects that the high swirl produced by the single-rotating propfan would have on the gas generator intake air. Accordingly in 1984 NASA, Lockheed-Georgia, Hamilton Standard, UTRC, and Boeing tested several types of inlets (fig. 45) in a Lockheed tunnel to determine propfan wake effects. The results indicated that a single-scoop inlet with a boundary layer diverter had the best total pressure recovery with acceptable inlet distortion.

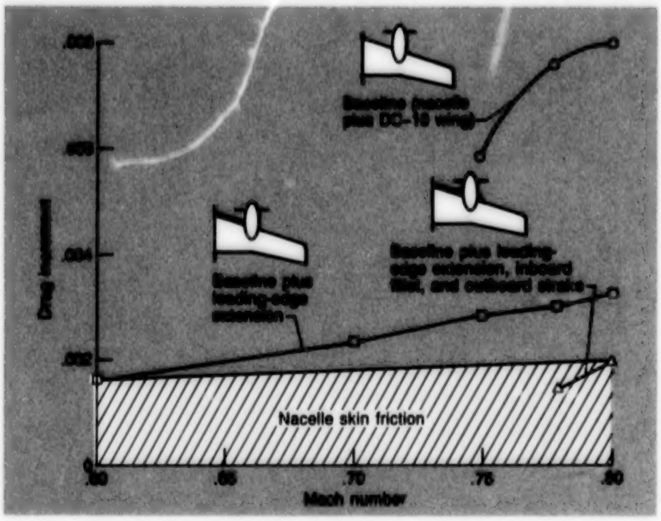


Figure 43.—Effect of wing contouring—with powered models and under-the-wing nacelle.

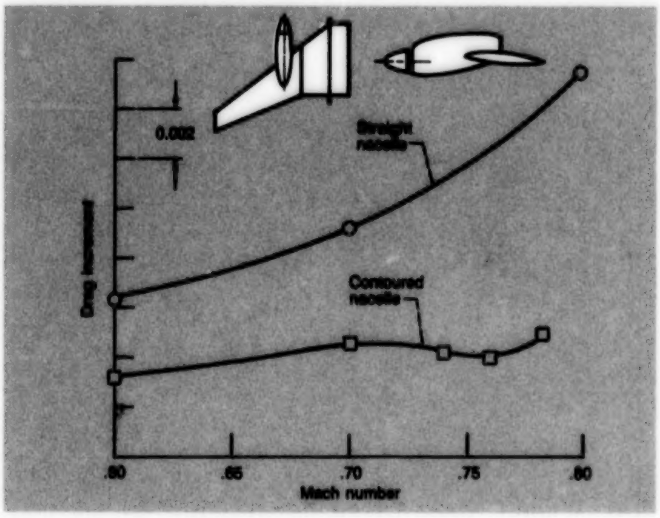


Figure 44.—Effect of nacelle contouring—with unpowered models and over-the-wing nacelle.

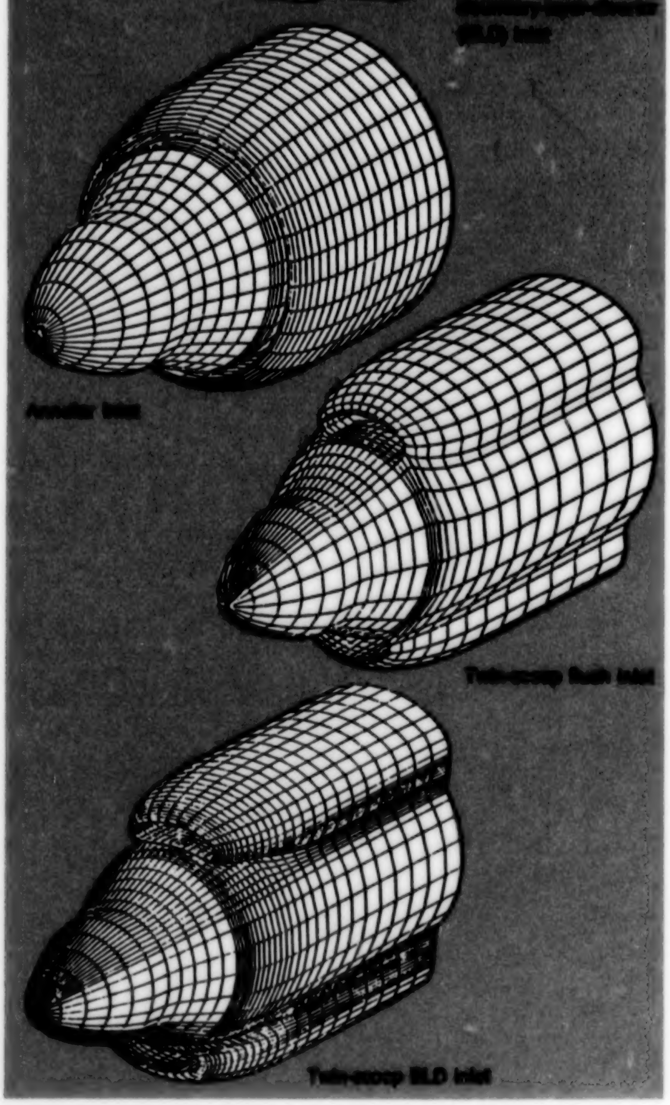

Flush inlet
Boundary-layer-diverter (BLD) inlet
Annular inlet
Twin-scoop flush inlet
Twin-scoop BLD inlet

Figure 45.—Propfan inlet configuration tested.

In 1985 tests were conducted in the UTRC 14-foot tunnel to measure inlet pressure recovery, inlet distortion, and the effects of inlet backpressure on blade stress. Several propfan-to-inlet spacings were tested. Results showed that spacing of about one blade chord offers the best combination of high inlet recovery and low blade stress. The single-scoop inlet (fig. 46) was positioned high enough to miss the hub boundary layer, and the short duct had slightly over 4 percent pressure distortion, well within the capability of an average gas generator. The single scoop avoided the boundary layer ingestion that occurs with lower profile inlets and was easier to build and contour into the nacelle than the twin-scoop, boundary-layer-diverter inlet.

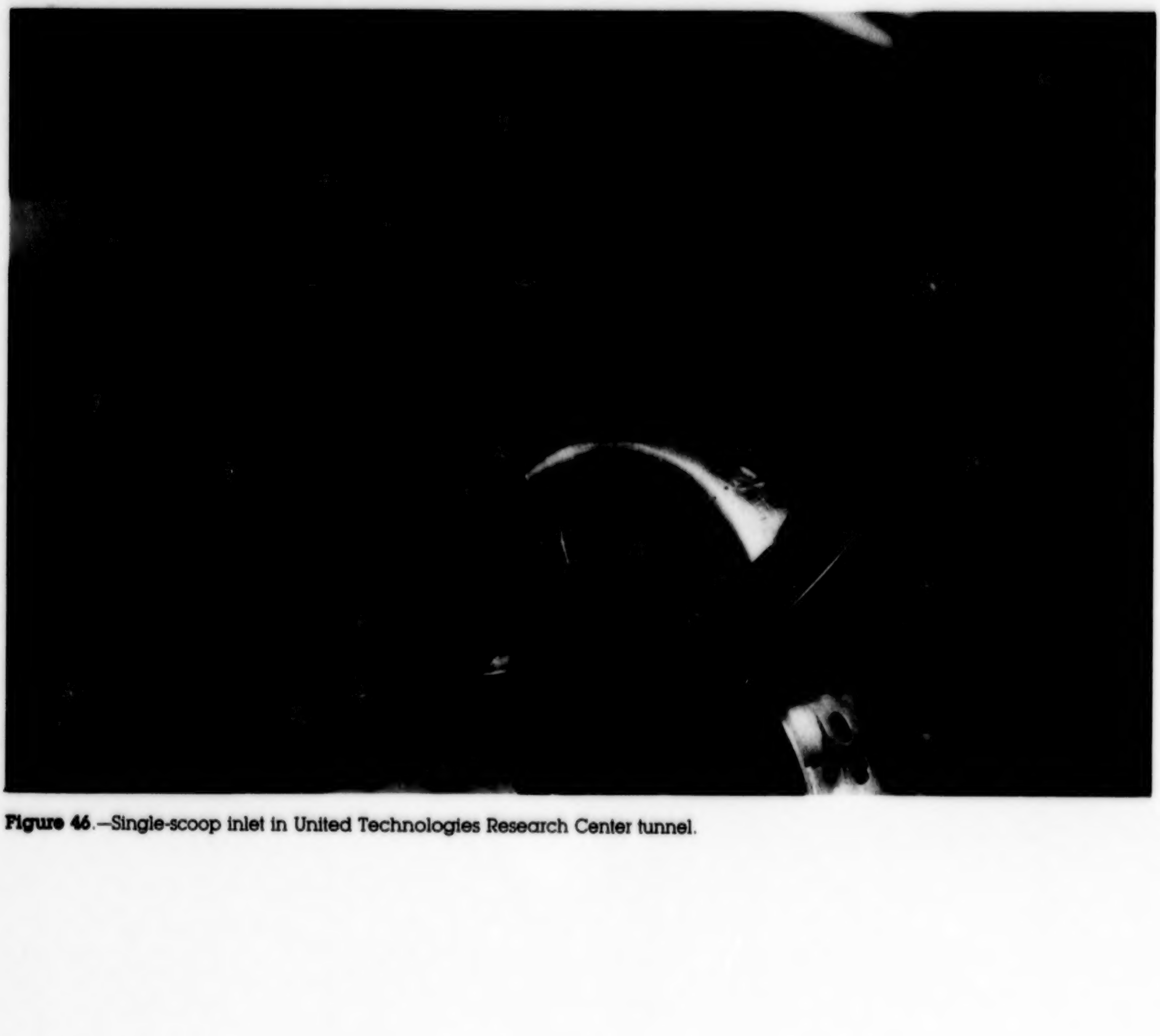


Figure 46.—Single-scoop inlet in United Technologies Research Center tunnel.

Drive System Technology

Advanced turboprop applications require power levels higher than those that are available for commercial applications. Both single- and counterrotating propfans require gearboxes capable of transmitting 12,000 to 20,000 shaft horsepower and advanced pitch-change mechanisms capable of controlling 8 to 10 highly loaded blades. Also such gearboxes and pitch-change mechanisms should be compact, lightweight, efficient, and easily maintained. NASA contracted General Electric, Pratt & Whitney, and Detroit Diesel Allison to study the problems of gearbox and pitch-change technology. Each item would be addressed (fig. 47) under the Advanced Propfan Engine Technology (APET) Project.

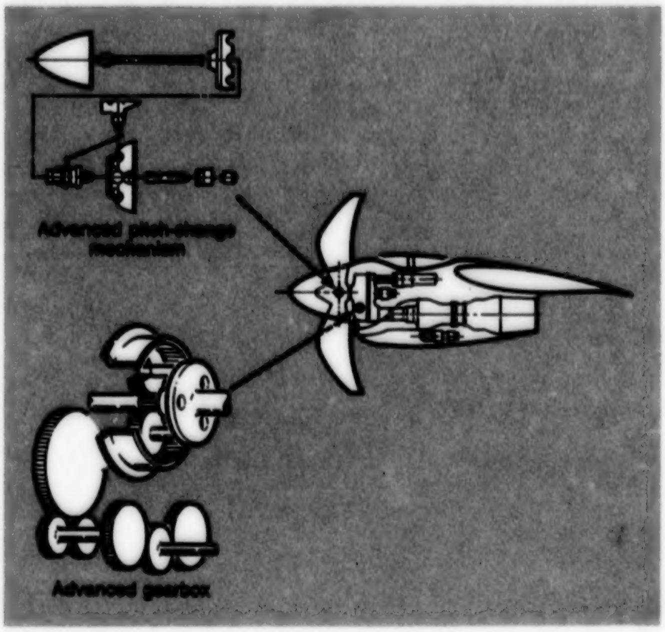


Figure 47.—Elements of Advanced Propfan Engine Technology (APET) Project.

APET studies evaluated the gearbox and pitch-change technology needs for an advanced turboprop propulsion system to be used on a 120-passenger short-range commercial transport. The studies showed a 20-percent fuel saving for a single-rotating propfan and a 31-percent fuel saving for a counterrotating propfan over an advanced turbofan engine. They also identified the need for long-life, low-maintenance gearboxes in commercial airliners.

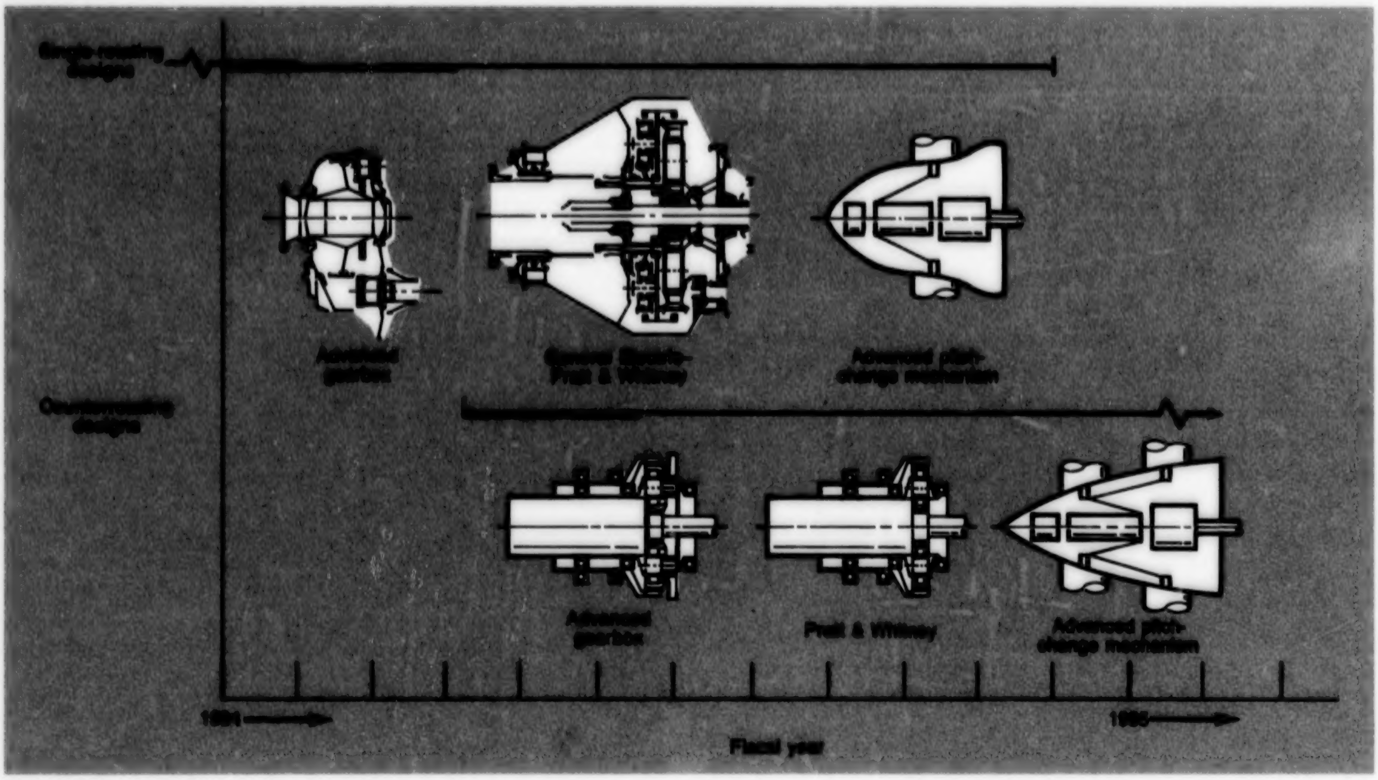

Single-rotating designs
Advanced gearbox
General Electric–Pratt & Whitney
Advanced pitch-change mechanism
Counterrotating designs
Advanced gearbox
Pratt & Whitney
Advanced pitch-change mechanism
1984
1985
Fiscal year

Figure 48.—Designs produced in APET studies.

The APET studies were extended in 1984 to include design studies of single- and counterrotating gearboxes and pitch-change mechanisms, as shown in figure 48. The resulting gearbox designs involved a number of gear arrangements that could satisfy both single- and counterrotating needs. Using current materials and lubricants, designs were made for 12,000 shaft horsepower. Assuming moderate advances in materials and methods, a design was produced that was 15 percent lighter than the best conventional designs. Both electromechanical and hydraulic pitch-change designs were considered. The results showed that gearboxes and pitch-change mechanisms for advanced turboprops were within the capability of today's technology. However, a general recommendation was that a major program, the Advanced Gearbox Technology (AGBT) Project, should be undertaken to design, fabricate, and test a modern gearbox.

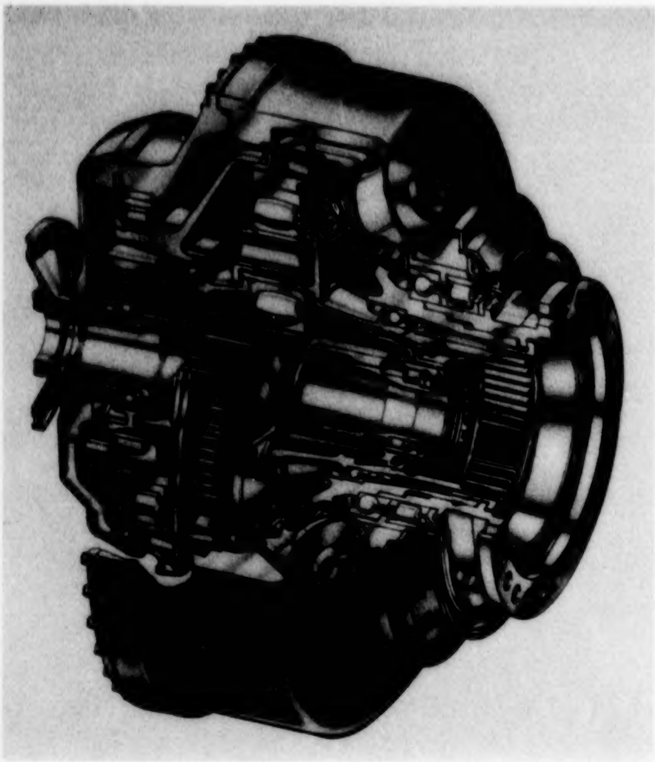


Figure 49.—Advanced counterrotating gearbox from Advanced Gearbox Technology (AGBT) Project.

Accordingly contracts were awarded by Lewis in 1984 to Allison and Pratt & Whitney to design and test an advanced counterrotating gearbox having a mean time between unscheduled removal of 20,000 to 30,000 hours and a 10,000- to 16,000-shaft-horsepower capability (fig. 49). The gearbox was to be better than 99 percent efficient, lightweight, and easily accessible and have low initial and maintenance costs. Both manufacturers completed the gearbox designs and fabrication, but before the Pratt & Whitney gearbox could be run, funding limitations forced NASA to halt the effort. Allison, however, chose to continue the program at their own expense. By 1986 Allison had completed 17 hours of testing in their own facility (fig. 50). All parts were in excellent shape at the post-test teardown. Because Allison planned to use a similar gearbox design in their counterrotating engine, they ran an additional 50 endurance hours in 1987 to verify the design before building the flight-weight engine gearbox. Their testing indicated that the gearbox design was on the right track.

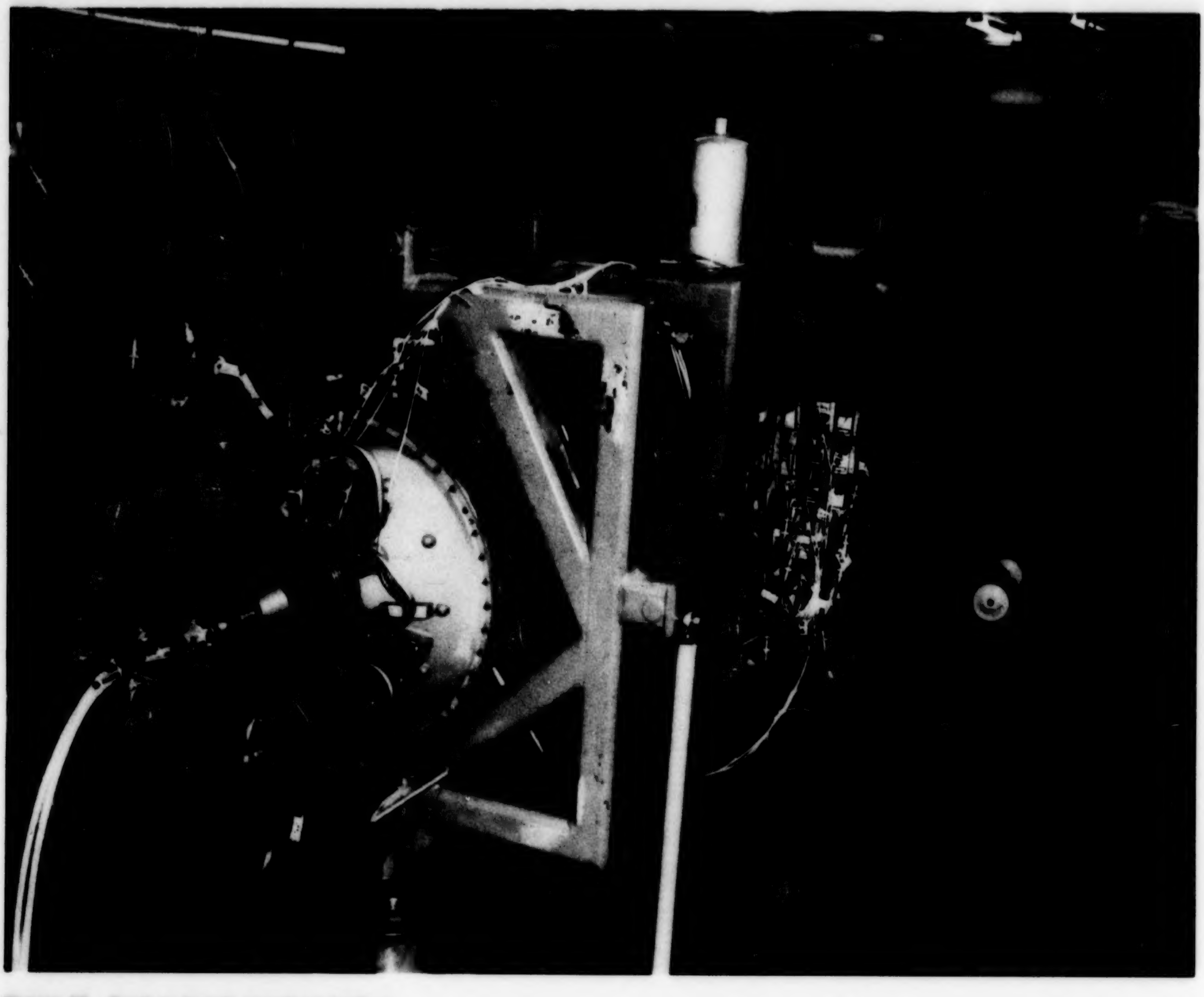


Figure 50.—Back-to-back gearbox testing.

Turboprop Aircraft Studies

During the course of the ATP Project several studies were performed by airframers to continue to assess the turboprop's potential for both civilian and military aircraft installations. Updated propfan characteristics were obtained from ongoing tests and analyses as input to the study efforts.

McDonnell Douglas DC-9/MD-80 Study

In mid-1979 Ames contracted McDonnell Douglas to evaluate the installation of single-rotating propfans on a DC-9/MD-80 aircraft. The various installation locations studied are shown in figure 51.

The fuel saving ranged from 22 to 25 percent for the turboprop derivatives relative to an MD-80 powered with an advanced-technology, pylon-mounted turbofan. An important conclusion from this study was that the aft-mounted turboprop installation was competitive with the wing-mounted installation.

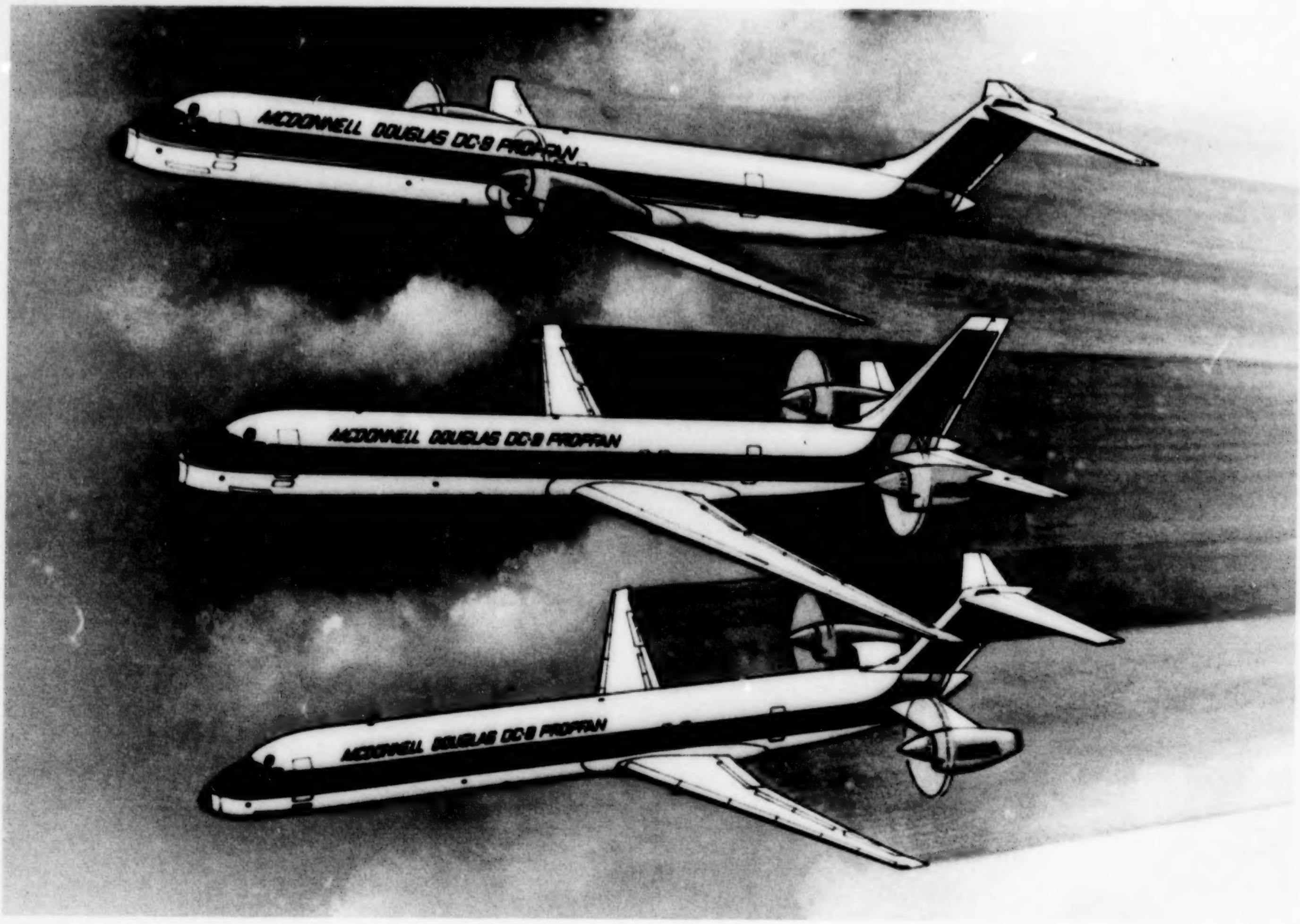

MCDONNELL DOUGLAS DC-9 PROPFAN
MCDONNELL DOUGLAS DC-9 PROPFAN
MCDONNELL DOUGLAS DC-9 PROPFAN

Figure 51.—Various turboprop installations on McDonnell Douglas DC–9.

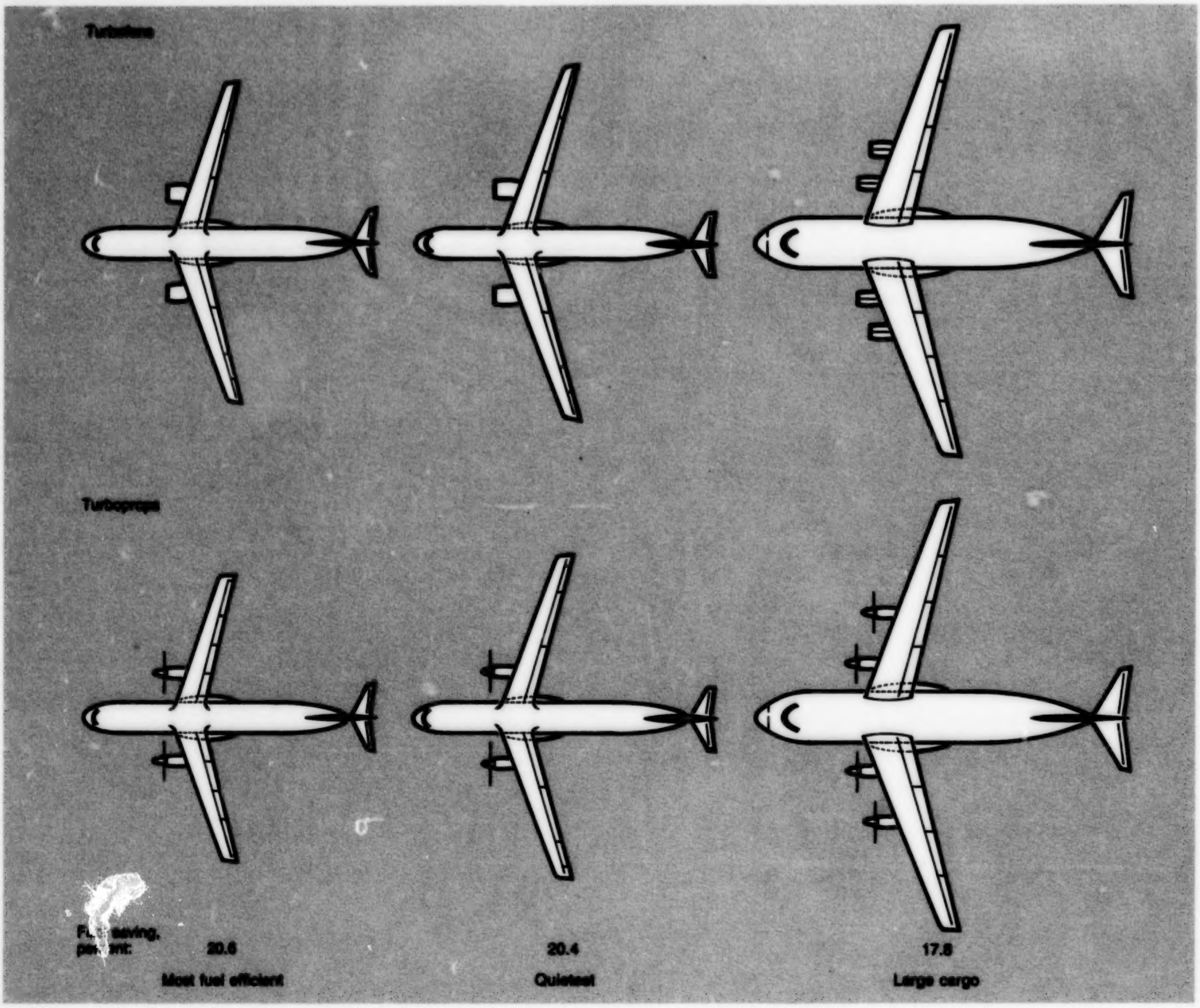


Figure 52.—Lockheed-Georgia advanced cargo aircraft configurations.

Lockheed Cargo Aircraft Study

In January 1980 Langley contracted Lockheed-Georgia to study advanced cargo aircraft applications. Figure 52 shows the best configurations defined for a 2295-nautical-mile mission using single-rotating propfans. The most fuel-efficient aircraft would use 20.6 percent less fuel than an equivalent-technology turbofan aircraft. Reducing propfan tip speed, blade loading, and blade number produced the quietest aircraft. Its noise print was about 15 percent smaller than the noise print of the most fuel-efficient aircraft, and it burned slightly more fuel. Lockheed-Georgia concluded that a turboprop can meet FAR–36 noise limits while using substantially less fuel than an advanced turbofan. Because of the greater thrust lapse rate the turboprop can also operate out of a 25 percent shorter airfield.

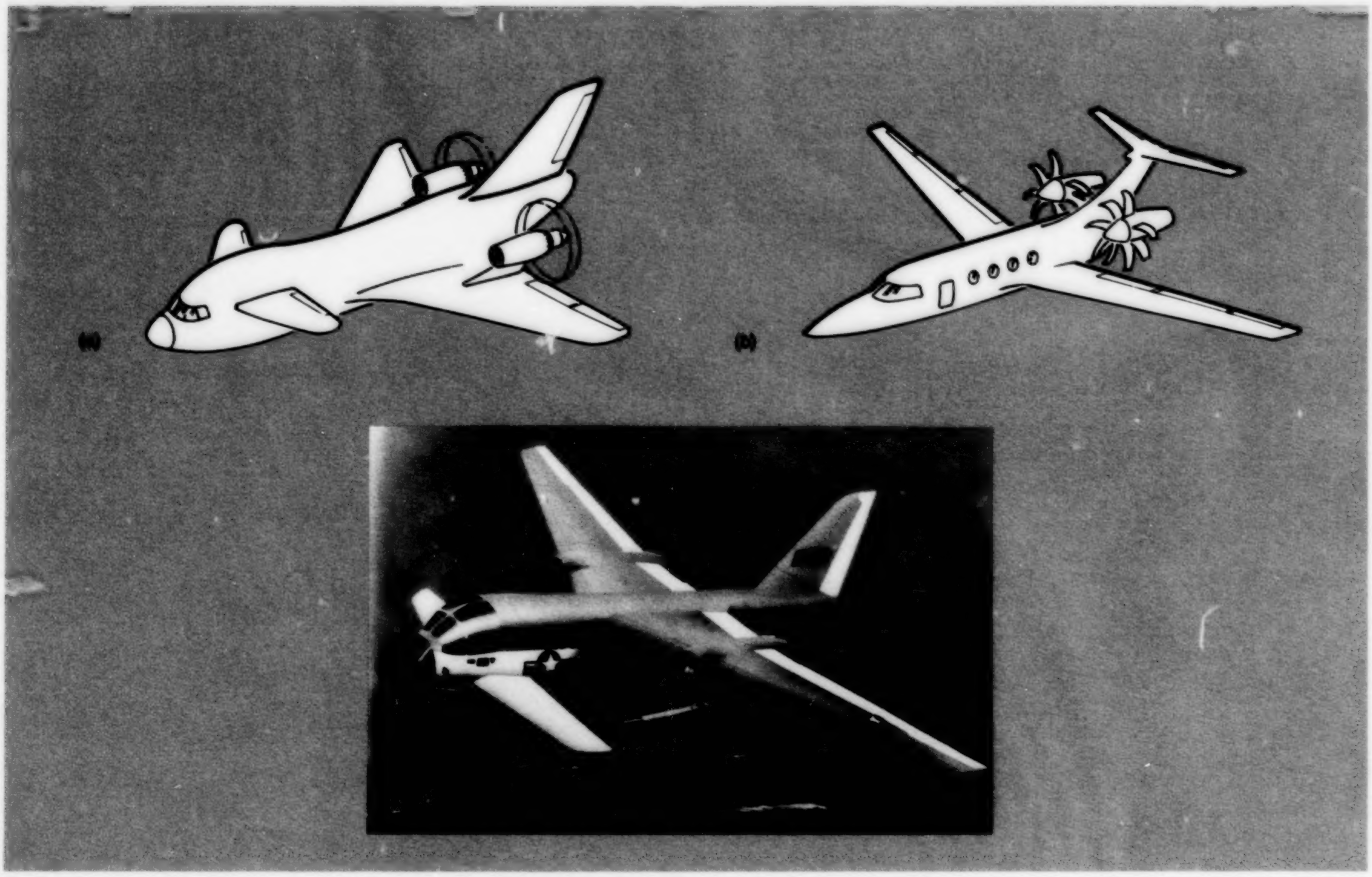


Figure 53.—Configurations resulting from Multiple-Application Propfan Studies. (a) Advanced tactical transport—McDonnell Douglas. (b) Eight-passenger business aircraft—Beech Aircraft. (c) Multimission, carrier-based aircraft designed for conventional, short, or vertical takeoff and landing—Boeing, Grumman, and Lockheed.

NASA Multiple-Application Propfan Studies

Lewis awarded contracts to study small business applications of advanced turboprops (fig. 53) to two airframe manufacturers, McDonnell Douglas and Beech Aircraft. These companies compared the performance of propfan and turbofan powerplants on advanced conceptual aircraft. The wing-mounted counterrotating pusher with 13.4-foot-diameter, six-blade propellers selected by McDonnell Douglas would use 27 percent less fuel than an equivalent-technology turbofan. Beech Aircraft's study of a single-rotating aft-fuselage-mounted turboprop showed that for Mach 0.7 to 0.8 cruise the fuel saving would be 16 percent over an advanced turbofan and 33 percent over current installations. However, because the initial costs projected for the turboprop were higher than equivalent-turbofan costs, the study showed an unfavorable return on investment.

Multiple-Purpose Subsonic Naval Aircraft Studies

Under NASA Lewis technical direction the Navy funded three airframe manufacturers, Boeing-Wichita, Grumman, and Lockheed-Georgia, to study multiple-purpose, subsonic, carrier-based aircraft as an extension of the civilian multiple-application propfan studies. Boeing selected a tanker configuration as their multimission aircraft; Lockheed, an armed, airborne, early-warning aircraft; and Grumman, a carrier onboard delivery aircraft. In general the studies determined that there were advantages in mission length or loiter time from using turboprop propulsion in place of turbofans. The configurations recommended are shown in figure 54.

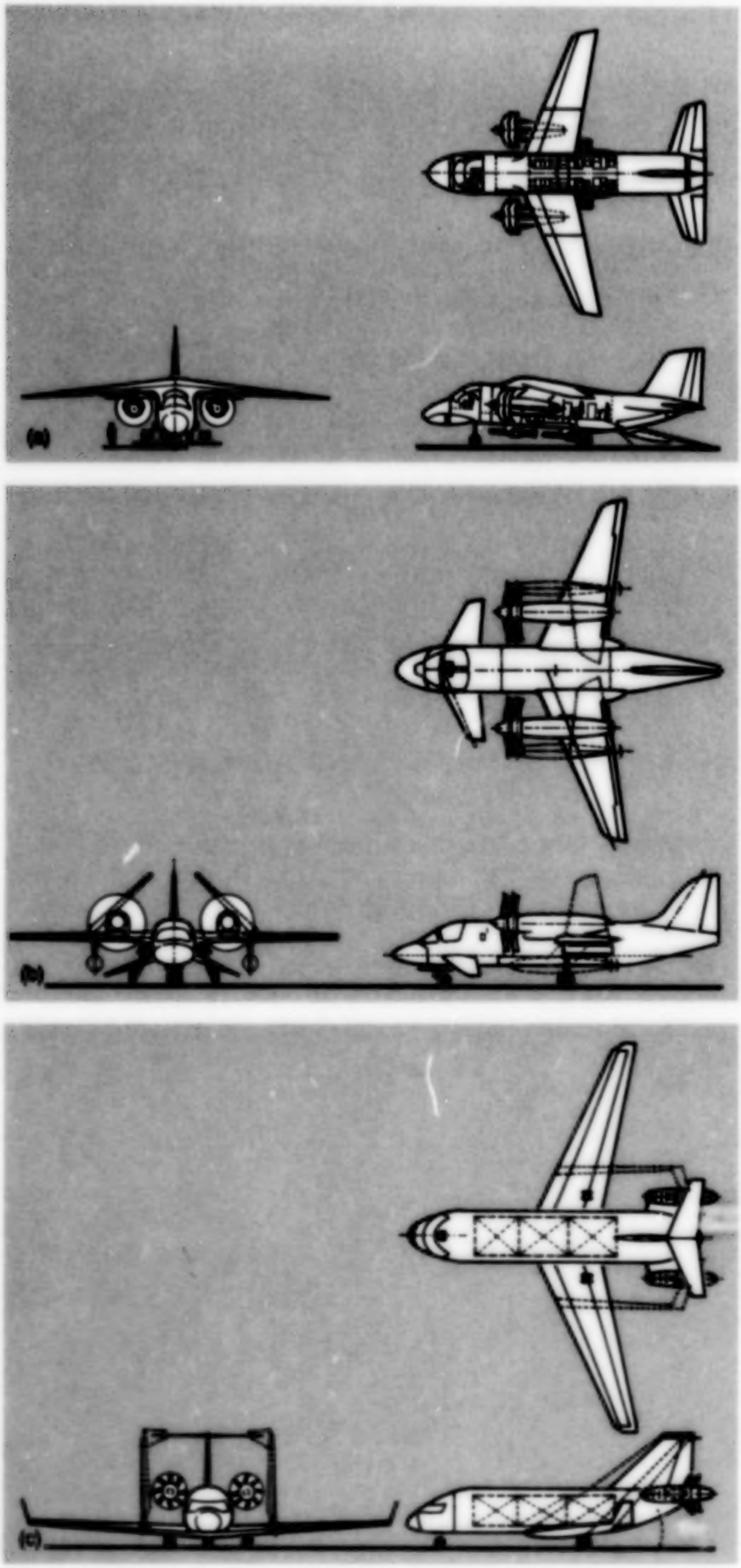


Figure 54.—Configurations resulting from Multiple-Purpose Subsonic Naval Aircraft Studies. (a) Tanker—Boeing. (b) Armed, airborne early-warning aircraft—Lockheed. (c) Carrier onboard delivery aircraft—Grumman.

Single-Rotating Turboprops

Large-Scale Advanced Propfan Project

Previous scale-model work and code development established the basis for the structural, acoustic, and aerodynamic design procedures needed for advanced turboprops. However, the design methodology was unproven for large-scale propfans that used lightweight blade construction. It was clear that complex testing of a large-scale propfan would be necessary to validate the structural integrity of these advanced designs.

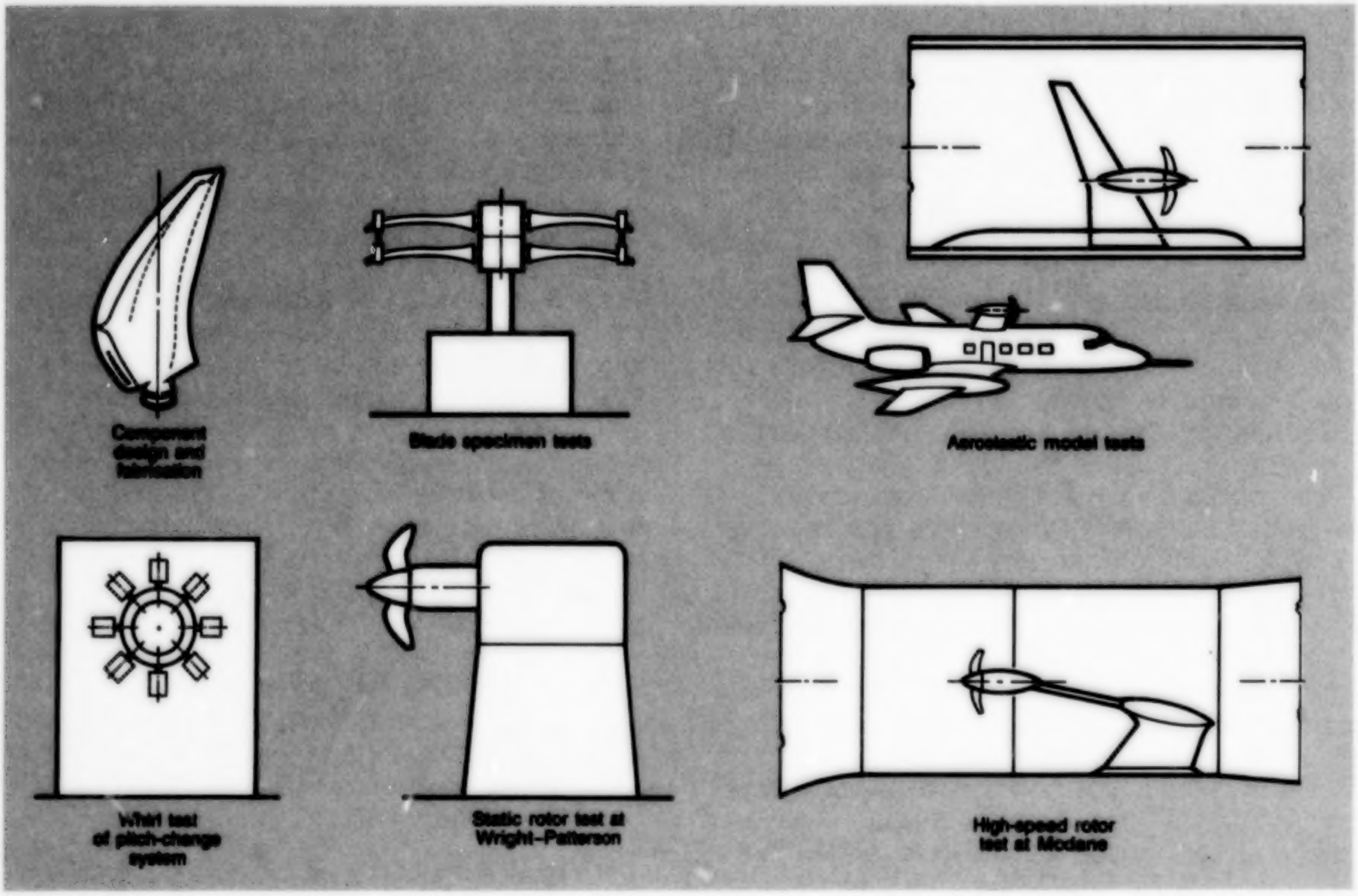

Component
design and
fabrication
Blade specimen tests
Aeroelastic model tests
Whirl test
of pitch-change
system
Static rotor test at
Wright–Patterson
High-speed rotor
test at Modane

Figure 55.—Major activities in Large-Scale Advanced Propfan (LAP) Project.

To accomplish this, the Large-Scale Advanced Propfan (LAP) Project was defined to design, fabricate, and ground test a large-scale propfan with a pitch-change mechanism and to provide propfan assemblies for subsequent flight testing. The blades were flightworthy (resistant to foreign object damage, durable, lightweight, efficient, etc.) and large enough to have mechanical characteristics representative of full-size production articles. The LAP tests would thus provide a data base for future propfan design. The LAP Project layout, starting with the design and proceeding to the final proof tests prior to the flight testing part of the ATP Project, is shown in figure 55.

Structural Design

As a prelude to the LAP Project NASA in 1980 began a design study of large-scale propfan blades with Hamilton Standard. Various constructional concepts were considered as shown in figure 56. Solid metal and composite blades were evaluated but rejected, primarily because of weight.

The most promising concept was a hollow shell containing a metal spar. This structure, which was used in all Hamilton Standard propellers for new commuter aircraft, had proven to be safe, reliable, and lightweight. With this construction foreign object damage problems inherent in earlier solid aluminum blades would be avoided by protecting the single load-bearing spar with an aerodynamically shaped fiberglass shell (fig. 57). Furthermore using this construction technique for large-scale propfans averted the need to develop new fabrication processes and thus enhanced the probability of initial success and industry acceptance.

As part of this initial design study several large-scale configurations were analyzed that had external shapes like the subscale models that had been tested: SR–2, SR–3, SR–5, and a 10-blade version of the SR–3. The results of this analysis showed that blades with very high sweep angles (like the SR–5) would require advanced materials and fabrication methods to satisfy structural requirements.

In 1981 Hamilton Standard was awarded a contract to design a large-scale, single-rotating propfan that would be suitable for flight testing. Researchers determined that a 9-foot-diameter propfan was close enough to commercial size to maintain realistic scaling of the structural cross section and thus eliminate concerns about further upward scaling of structural test data. This size matched, with minimal modifications, the power capabilities of the largest available turboshaft engine and gearbox (Allison model 570 industrial gas turbine and T56 gearbox).

A number of design iterations were required to arrive at a blade design that would satisfy stress and flutter requirements yet retain good aerodynamic and acoustic performance. The resulting SR–7L blade (fig. 58) was similar in shape to the SR–3 but had somewhat less sweep (41° versus 45°). Its power loading was slightly lower than the SR–3's, and its construction was spar–shell. The hub contained a hydraulic pitch-change mechanism, and the spinner was contoured to minimize the possibility of hub choking.

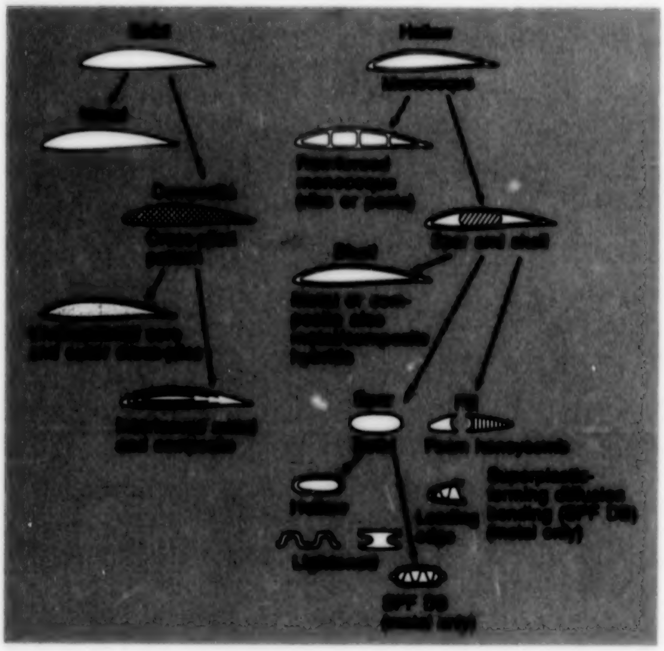

Solid
Hollow
Monocoque
Composite
Reinforced monocoque (ribs or posts)
Spar and shell
Shell
Spar
Fill
Foam honeycomb
Hollow
Superplastic-forming diffusion bonding (SPF DB) (metal only)
Leading edge
Lightweight
SPF DB (metal only)

Figure 56.—Blade structural concepts evaluated.

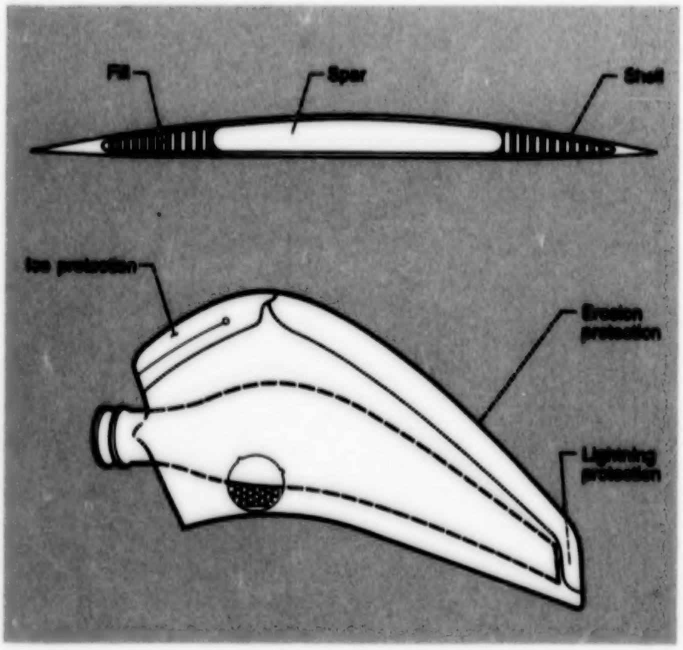

Fill
Spar
Shell
Ice protection
Erosion protection
Lightning protection

Figure 57.—Spar–shell concept selected for LAP blades.

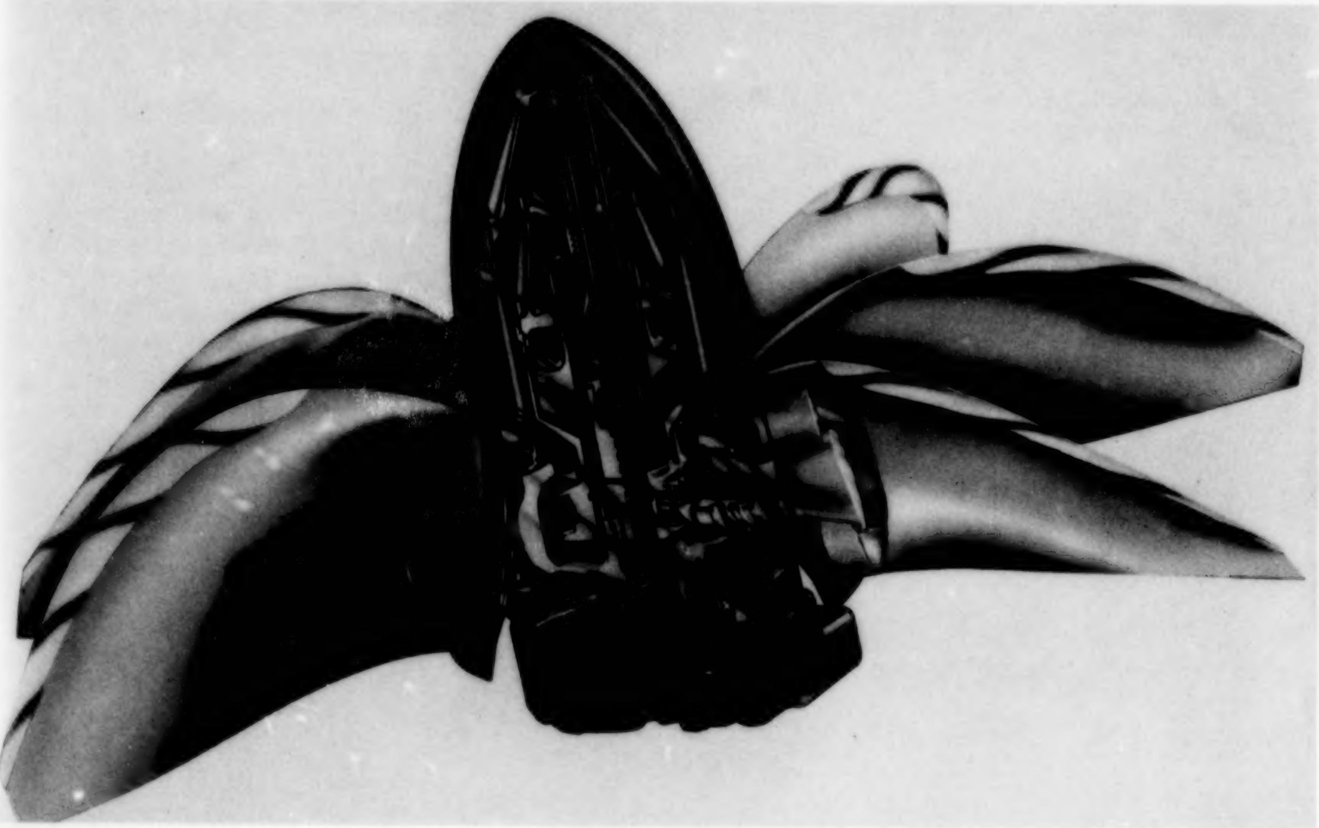


Figure 58.—Large-scale advanced propfan (LAP) assembly.

After a successful design was achieved, two SR–7L propfans with spinners, pitch-change mechanisms, hubs, and spare parts were fabricated by Hamilton Standard. Extensive structural and aeroelastic tests were planned to establish airworthiness. Blade vibration tests and hub retention tests with stub blades showed close agreement with design. During limited whirl testing the first hub and pitch-change system functioned well and was subsequently cleared for ground static tests at Wright–Patterson Air Force Base.

In early 1986 a complete test of the second hub assembly was conducted in the Hamilton Standard whirl rig. Approximately 20 hours of functional and endurance testing produced satisfactory results. This hub assembly with a new set of blades was shipped to Rohr's Brown Field facility in Chula Vista, California, for a powered ground test that was performed as part of the flight testing.

Aeroelastic Model

As part of the LAP Project a 2-foot-diameter aeroelastic model called the SR–7A was built and tested to establish confidence in the blades' aeroelastic characteristics before the large-scale SR–7L tests and to measure performance and acoustic levels. Vibration and holography bench tests showed that the blades' natural frequencies and mode shapes were close to design analysis. These blades, assembled into an eight-blade hub, gave a system response similar to that projected for the full-size SR–7L blade. The SR–7A blade and assembly are shown in figure 59.

In April 1985 the assembly was installed in the Lewis transonic wind tunnel for high-speed flutter clearance and for a preliminary measure of noise levels. Tests were made to Mach 0.9 with angles of attack to 8°. Since there was no sign of flutter at high speed in the operating range, the flutter code was determined to adequately represent the structural response at cruise conditions. Although a strong forced-vibration response to the angle-of-attack tests was measured, it was not as strong as expected and the preliminary noise levels were somewhat lower than expected.

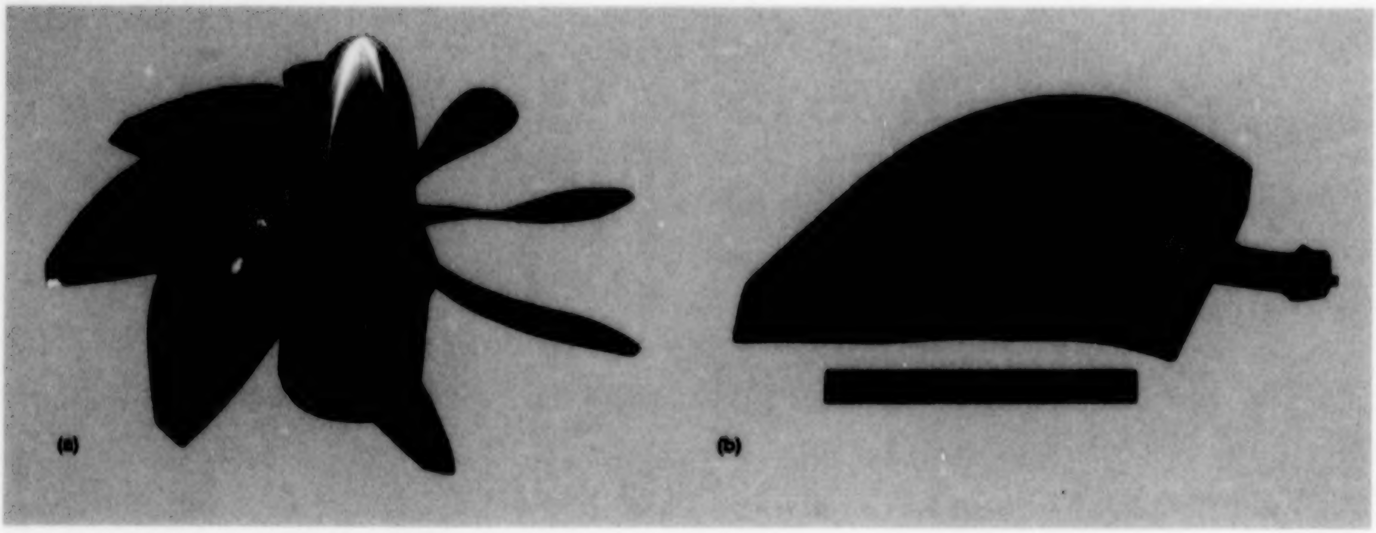


Figure 59.—SR–7A aeroelastic model blade and test assembly. (a) SR–7A model assembly. (b) SR–7A blade.

In the next test series the scale-model SR–7A was installed in the Lewis low-speed wind tunnel for tests of the flutter characteristics at takeoff conditions. Data were obtained to Mach 0.2 and yaw angles from 0° to 20°. No stall flutter was encountered, but a stall buffet region was observed with high loadings at static flow conditions. At slight forward velocity the buffeting disappeared and the blade was subsequently flutter cleared. This agreed with the later large-scale static test at Wright–Patterson Air Force Base and gave confidence that the flutter codes were equally valid for the 9-foot propfan blades.

In January 1986 Lewis began acoustic testing on the SR–7A in the low-speed wind tunnel at takeoff and approach conditions (fig. 60). Data were recorded to 15° angle of attack with a model wing adjustable for varying degrees of sweep. Analysis showed that fundamental tone noise can increase 5 to 10 decibels at 10° angle of attack for certain sweep settings. The up-inboard rotation was confirmed as the quietest swept-wing configuration.

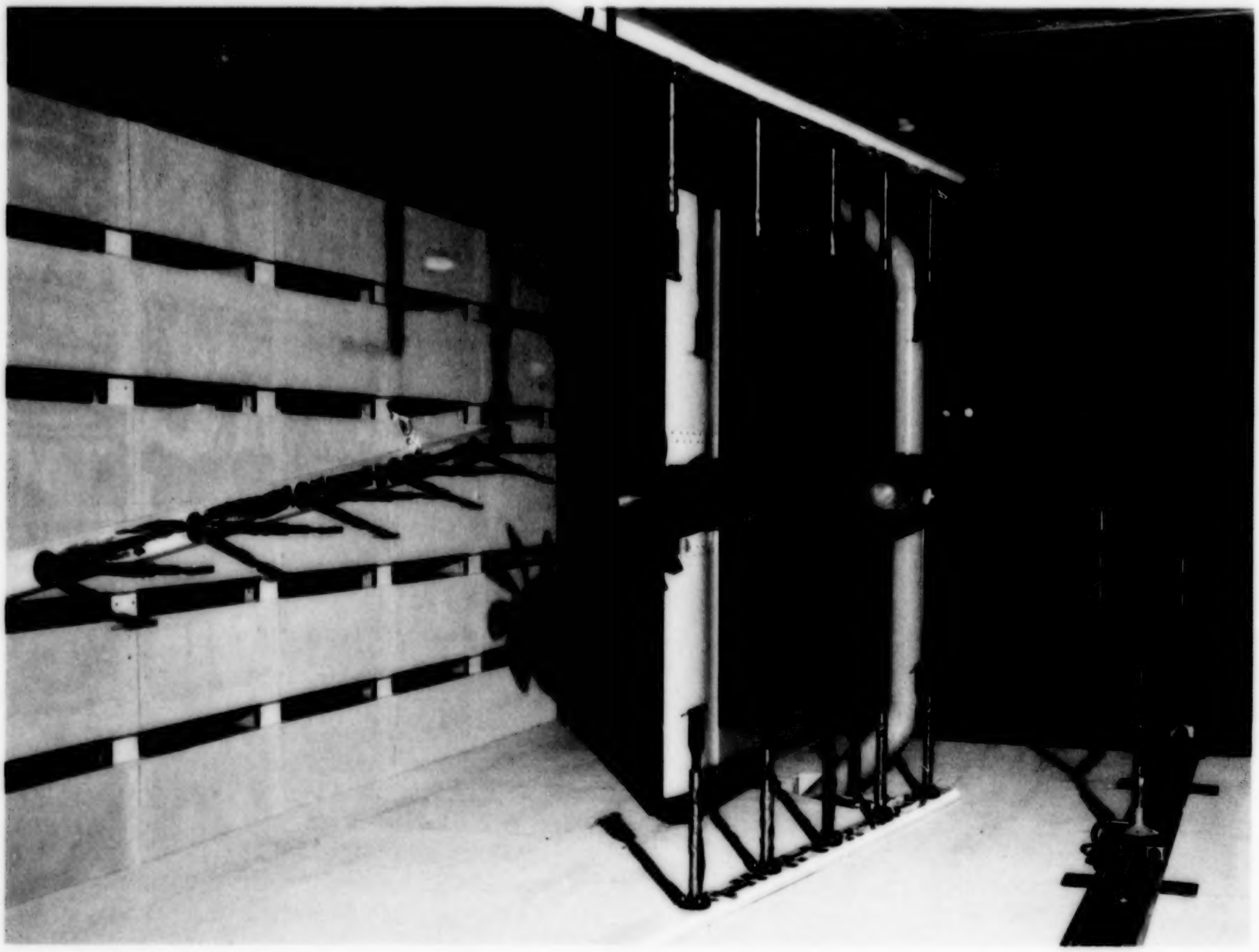


Figure 60.—Acoustic testing of SR–7A in Lewis low-speed wind tunnel.

The final test series was performed in the Lewis transonic wind tunnel starting in early 1987 to record performance data and to complete the high-speed acoustic measurements. By the spring of 1987 all acoustic and performance tests were completed on the SR–7A. The data agreed favorably with the predictions and with earlier data. Owing to its lighter loading but lower sweep, the SR–7A was about as noisy as the SR–3, but slightly more efficient (79.3 versus 79.0 percent).

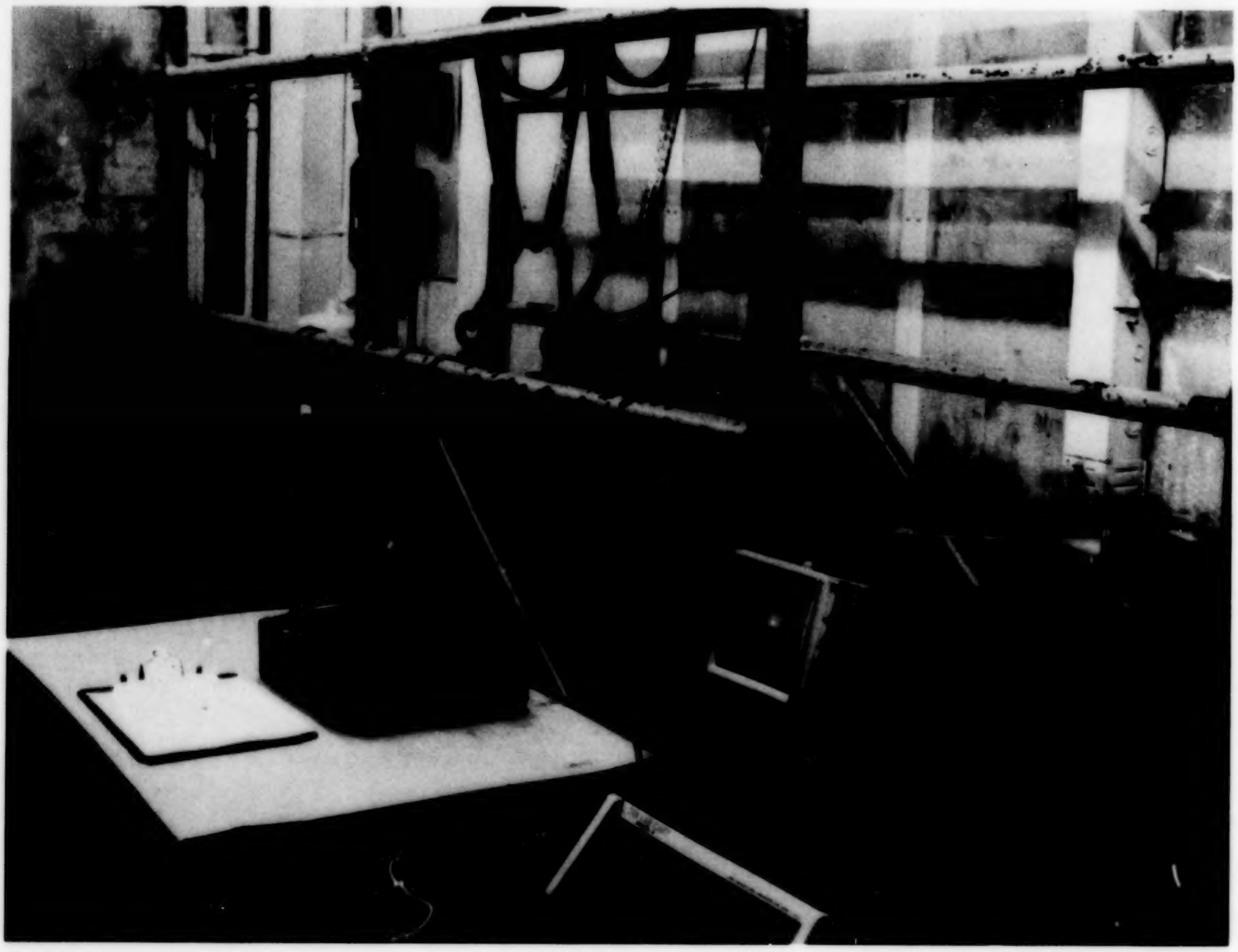


Figure 61.—Hamilton Standard's blade cyclic fatigue test machine.

Hamilton Standard Blade Cyclic Fatigue Tests

During September 1985 Hamilton Standard began a detailed series of fatigue tests on the propfan blades to qualify them for the flight test. The Hamilton Standard blade cyclic fatigue test machine is shown in figure 61. A two-blade configuration completed 110 million cycles with vibratory loads to 1.5 times the design spar stress. Further tests were performed on a four-blade configuration under a combined steady and vibratory load to 1.5 times the design spar stress for 70 million cycles. The major problem identified during testing was that the cavity foam separated from the fiberglass skin and subsequently cracked. The foam is not a structural element, but if it were used in a commercial blade, this problem would have to be corrected. Improvements were later made in the foaming process used during blade manufacture, and the incidents of foam separation decreased.

Figure 62.—Large-scale advanced propfan installed on Wright-Patterson Air Force Base test stand.

Static Tests at Wright–Patterson Air Force Base

Using the hardware from the first SR–7L, Hamilton Standard engineers built the first propfan assembly and tested it statically on a test stand at Wright–Patterson Air Force Base in Ohio (fig. 62). The objectives were to obtain static aerodynamic performance and blade stability data and to determine the functional characteristics of the propfan assembly under power. Tests were run to 1900 rpm (112 percent of design) and 102 percent of the design power (6000 shaft horsepower; 9000 pounds thrust). Over 300 data points were recorded to obtain blade-angle-versus-speed data. Performance was comparable to that of the aeroelastic scale-model rig (SR–7A).

The stall buffet that had been identified during scale-model tests in the low-speed wind tunnel also occurred with the SR–7L at high power settings. Stall buffet during takeoff is not expected to be a problem for flight testing or for commercial application since the power can be scheduled as a function of forward velocity to prevent blade stall at low velocities. In all other circumstances the blade stresses were low. There was no sign of stall flutter.

Blade deflections due to centrifugal and aerodynamic loads were measured with an optical system and a Lewis-developed laser system. Pressures on the surface of a specially modified blade were also measured during testing. Calculated deflections and pressure profiles showed a reasonable agreement with design.

The propfan assembly completed the test in good mechanical condition. Other than the same kind of foam-filler separation experienced during the blade endurance testing at Hamilton Standard, there were no problems. Consequently in November 1985 the propeller was shipped to Hamilton Standard to be prepared for the high-speed wind tunnel tests.

High-Speed Tests at Modane

High-speed testing was conducted in the S1 wind tunnel at Modane, France. This tunnel was chosen because it was large enough to test the full 9-foot-diameter assembly at Mach 0.8 and 12,000-foot-altitude conditions. However, since power was limited in the facility propeller drive system, full aerodynamic loading could not be achieved on the eight-blade SR–7L. Therefore two- and four-blade configurations as well as the eight-blade configuration were tested.

Structural dynamics, aerodynamic performance, and blade-surface static pressure tests were conducted at Modane for comparison with design codes and model test data. Two of the configurations and the pressure transducer locations are shown in figure 63. Testing started in early 1986. Data were recorded to Mach 0.34 and 109 percent of design rotational speed at power levels to 1160 shaft horsepower. Structural tests with the two-, four-, and eight-blade SR–7L showed no evidence of excessive forced vibration or classical flutter at various angles of attack. Because of the power limitations only the two-blade propeller could be run at high blade loadings, but the test results were reassuring for the flight tests. Although the data matrix was not completed owing to facility problems, some performance data and blade-surface static pressure measurements were recorded. These data confirmed the model data.

A second test series, conducted in February 1987, was limited to 13 days and allowed testing of only the two-blade SR–7L. A full matrix of steady and unsteady pressure profiles was recorded around the blade surface. The data verified the aerodynamic analyses.

The SR–7L LAP effort produced an advanced propfan assembly designed with modern methods and fully researched with full-size and scale-model rig data. With the completion of the LAP testing the propfan development work was finished, and the propfan assembly was delivered for the flight research testing to be performed in the next part of the ATP Project.

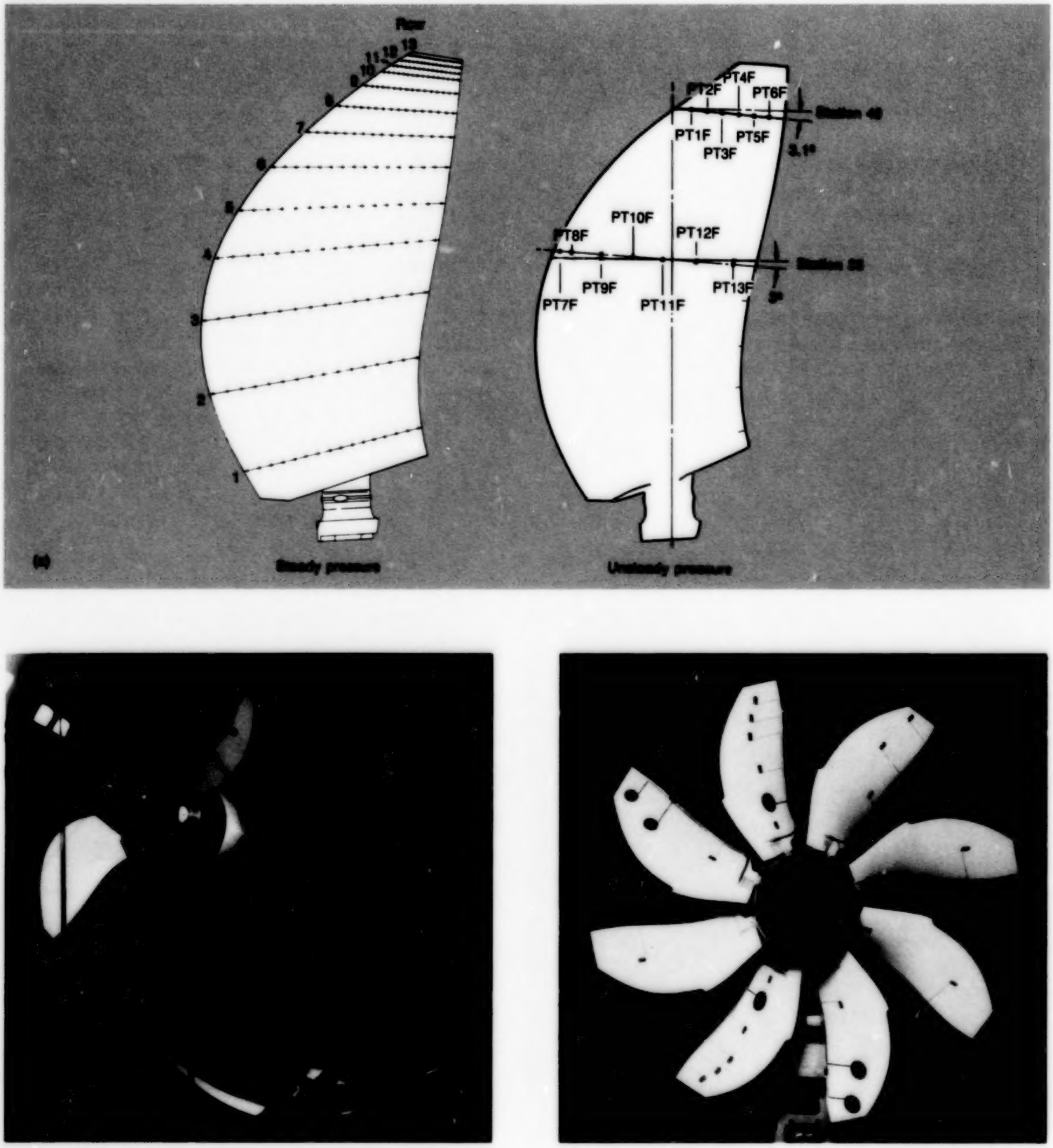

Row
13
12
11
10
9
8
7
6
5
4
3
2
1
PT4F
PT2F
PT6F
Station 40
PT1F
PT5F
PT3F
3.1°
PT10F
PT8F
PT12F
Station 25
PT9F
PT13F
3°
PT7F
PT11F
(a)
Steady pressure
Unsteady pressure

Figure 63.—Large-scale advanced propfans installed in Modane wind tunnel. (a) Transducer locations. (b) Two-blade model. (c) Eight-blade model.

Propfan Test Assessment Project

After static testing was completed under the LAP Project, the SR-7L propfan was further evaluated as part of a complete turboprop propulsion system in the Propfan Test Assessment (PTA) Project under contract with Lockheed-Georgia. The objectives of this project were to verify the structural integrity of the blading and to evaluate the acoustic characteristics of a large-scale propfan at cruise conditions. Because of the complexity of the flowfield and the interaction between the propfan and the aircraft, it was felt that the only accurate way to do this was with a full-scale flight test.

The PTA Project (fig. 64) was composed of several elements: combining a large-scale advanced propfan with a drive system and nacelle; proof testing this propulsion system at Rohrs' Brown Field facility; conducting a series of model tests to confirm aircraft stability and control, handling, performance, and flutter characteristics; modifying a Gulfstream II aircraft; and finally flight testing the propfan installed on the left wing of the modified aircraft.

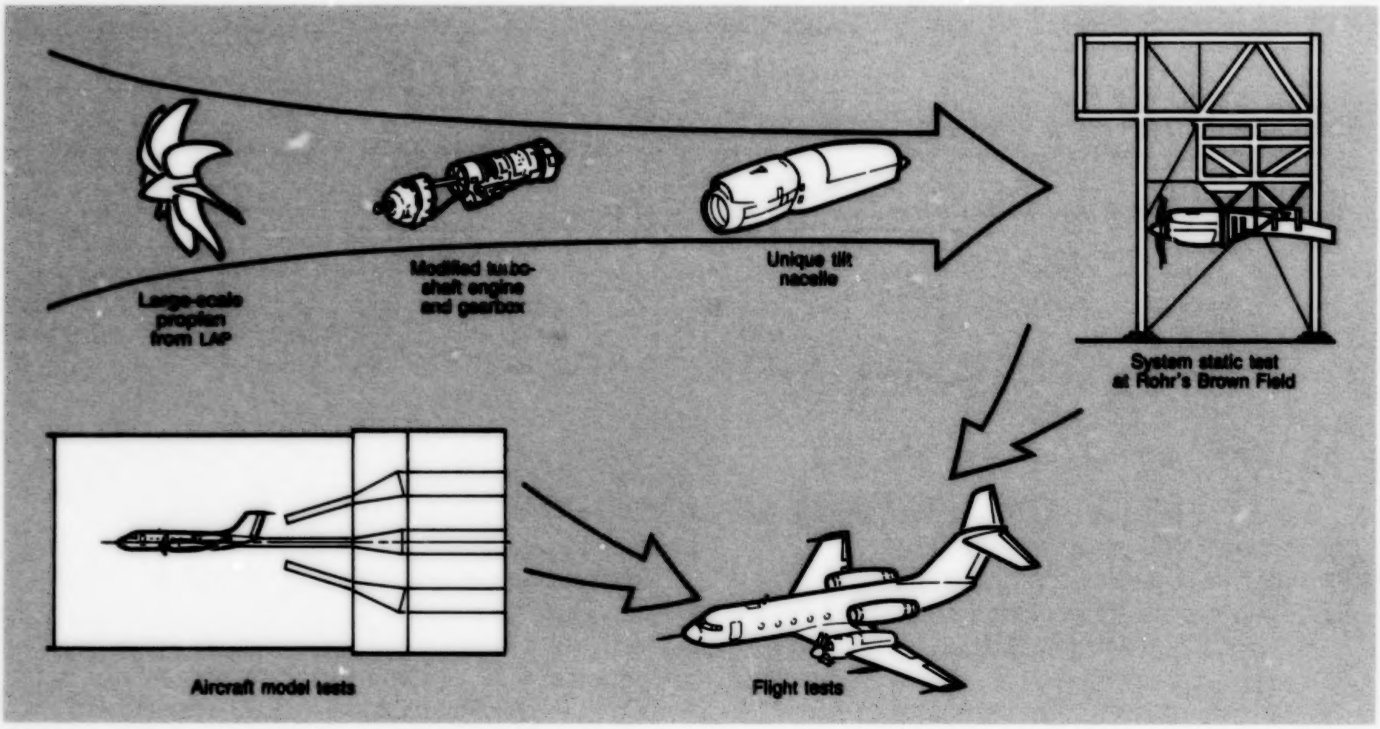

Large-scale propfan from LAP
Modified turbo-shaft engine and gearbox
Unique tilt nacelle
System static test at Rohr's Brown Field
Aircraft model tests
Flight tests

Figure 64.—Elements of Propfan Test Assessment (PTA) Project.

Hardware Modifications

The first task was to develop an airworthy drive system for the propfan assembly. Since the objective of the PTA Project was to test the propfan and not to develop a prototype propulsion system, existing hardware was used wherever possible to keep costs to a minimum while providing a reliable drive system to power the 9-foot-diameter SR–7L propfan. Therefore the Allison model 570 engine and T56 gearbox were selected as the most suitable combination to provide the 6000 horsepower needed.

Two Allison model 570 industrial gas turbines and three T56 gearboxes were modified. The engine control systems included a modified flight electronic control and a modified hydromechanical fuel control taken from the XT–701 helicopter engine. The flow area for the first-stage turbine had to be increased 3 percent, the inlet flange and struts were strengthened to support the gearbox, and a model 570 internal torquemeter was modified to provide a torque readout. The gearboxes were modified to reverse the direction of rotation and to change the gear ratio.

The engine modifications were completed and acceptance tests performed at an Allison altitude test cell starting in September 1985 (fig. 65(a)). In this test series the gas generators were tested for sea-level and altitude performance, light-off capabilities, endurance, and engine transient characteristics. Results showed an acceptable power margin over specifications and acceptable operability and transient performance. An endurance cycle of 60 hours was completed and altitude light-offs were verified to 10,000 feet.

Proof tests of the gearbox (fig. 65(b)) also began in September 1985 at Allison's new gearbox facility. Total test time for both gearboxes was over 720 hours with a 60-hour endurance test at power levels to 6000 horsepower. Teardown after testing showed the proposed flight test program was well within the capabilities of the modified T56 gearbox.

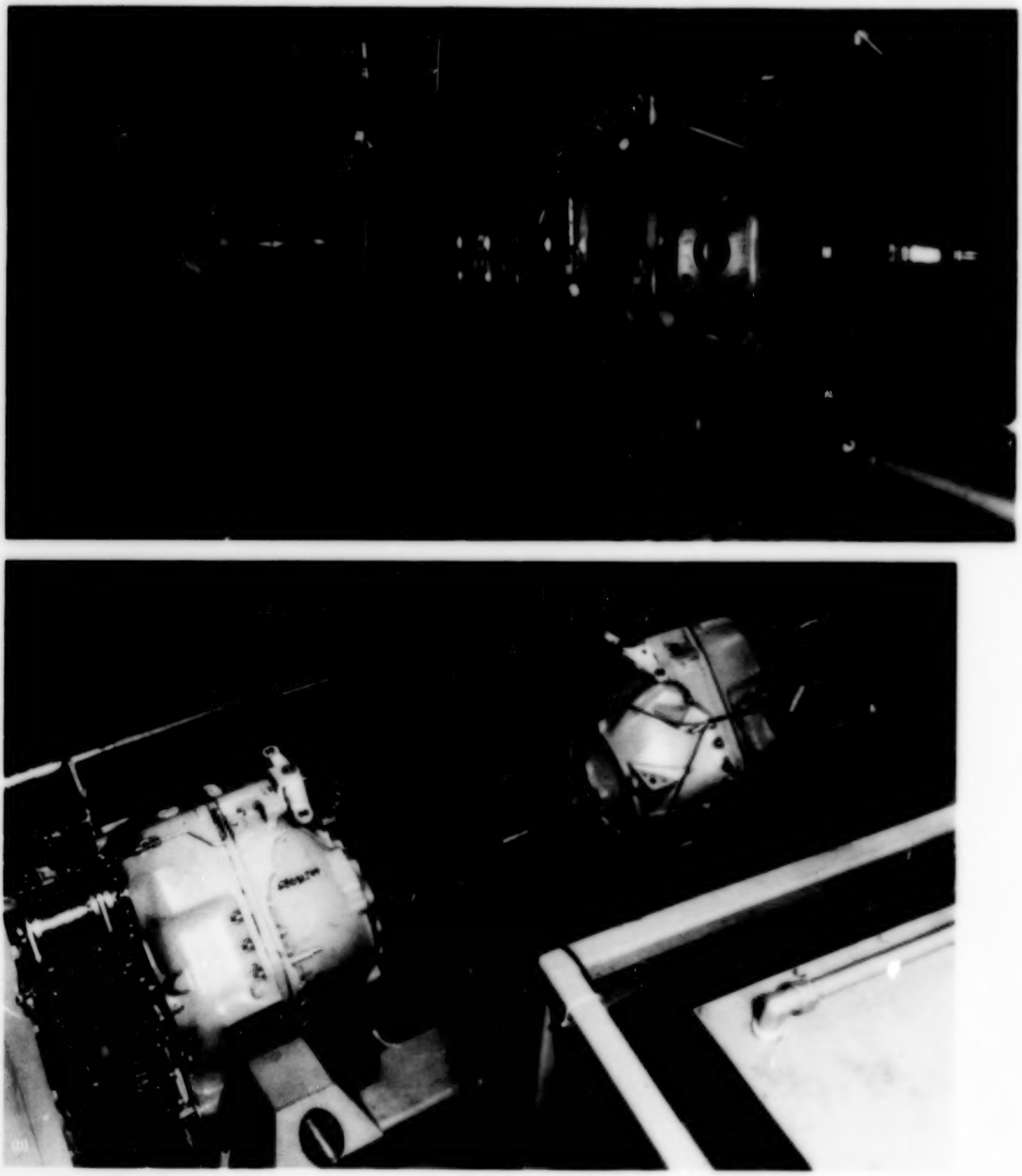


Figure 65.—PTA drive system components modified and tested at Allison. (a) Engine. (b) Back-to-back gearbox rig.

Supporting-Technology Wind Tunnel Tests

Earlier wind tunnel testing of a propfan–nacelle–inlet model under a joint NASA-industry test program had shown that a single-scoop inlet with a boundary layer diverter would provide acceptable performance for the PTA installation. These "flow-through" inlet model tests, however, investigated flow and pressure recovery only as far as the inlet throat. It was therefore necessary to build and test a model S-duct diffuser so that pressure recovery and flow distortion could be evaluated downstream of the inlet throat at the compressor face. In October 1984 Lockheed-Georgia completed tests of an S-duct diffuser model designed for the PTA installation. Diffuser airflow in this static test was induced by a tip turbine downstream of the diffuser. Airflow rates ranged up to and beyond the compressor-face design Mach number condition. The S-duct test apparatus with a bellmouth static inlet is shown in figure 66. The pressure recovery was 99 percent, and flow distortion levels were well within the limits specified by Allison for the compressor. These results, when combined with the inlet model test results (fig. 67), indicated that a 4-percent supercharging benefit from the propfan could be obtained at the compressor face for the total propfan–inlet–S-duct system.

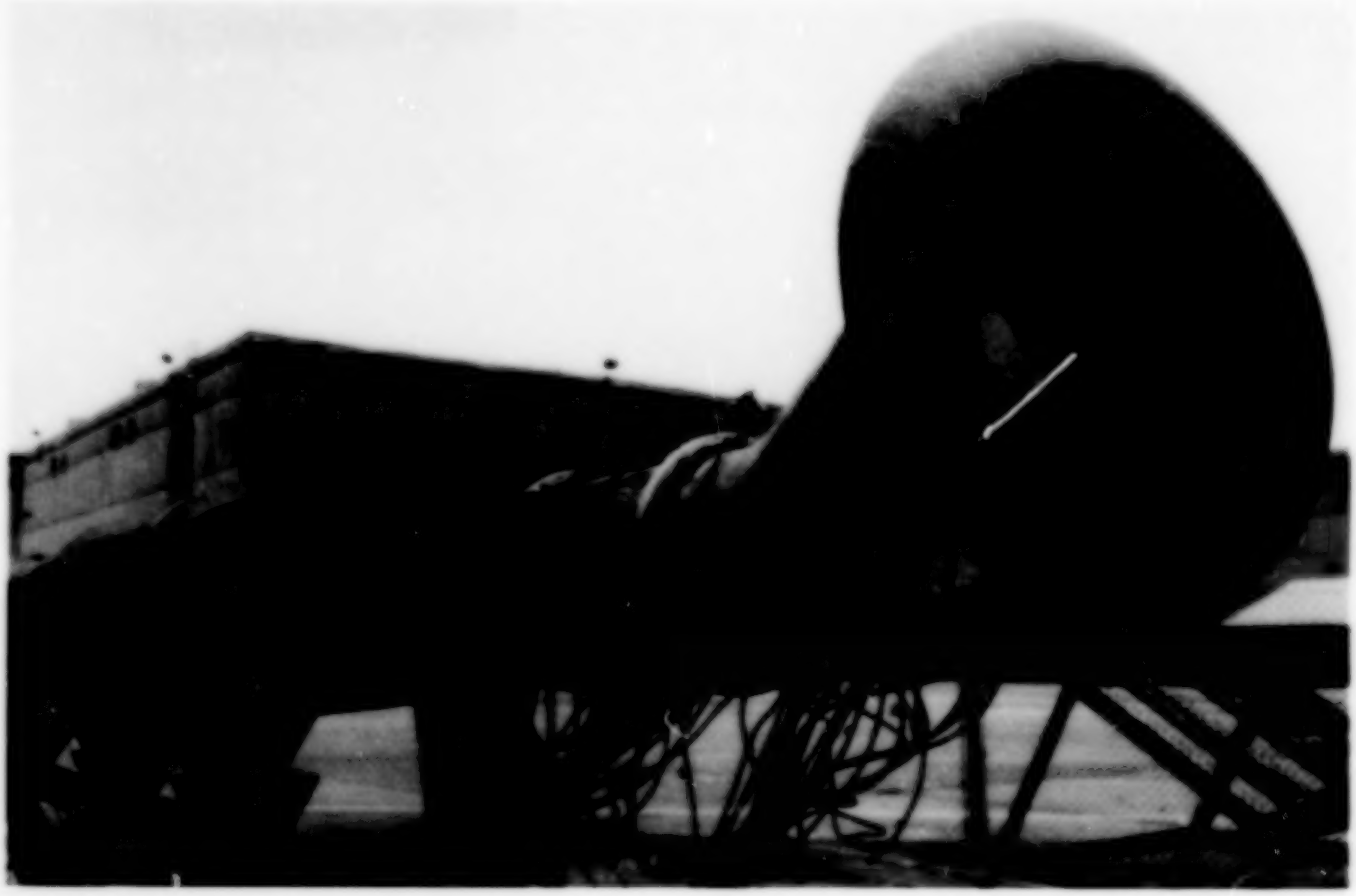


Figure 66.—S-duct test rig with propfan inlet-diffuser model.

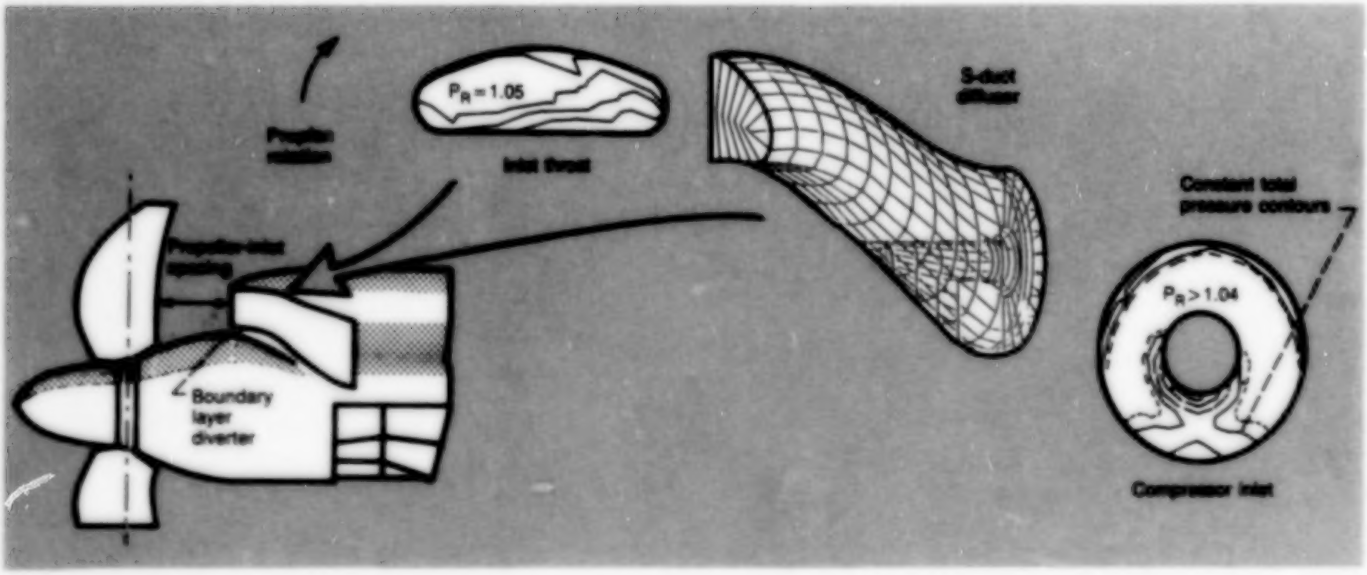

Propfan rotation
$P_R = 1.05$
Inlet throat
S-duct diffuser
Constant total pressure contours
Propeller-inlet spacing
$P_R > 1.04$
Boundary layer diverter
Compressor inlet

Figure 67.—Results of S-duct model tests.

Since the PTA aircraft was to be modified to accommodate a test engine and nacelle on the left wing and a static balance boom on the right wingtip, model aircraft wind tunnel tests were performed at NASA Langley to establish aircraft aeroelastic, stability and control, performance, handling, and flowfield characteristics in the propfan plane. A 1/9th-scale aeroelastic model of the PTA aircraft (fig. 68) was tested in August 1985 in Langley's 16-foot transonic dynamics Freon tunnel. The aircraft model was tested with a propfan model at speeds to Mach 0.9 and for several simulated fuel loading conditions. Test results confirmed that the aircraft was free of any aeroelastic instability throughout the planned flight test envelope.

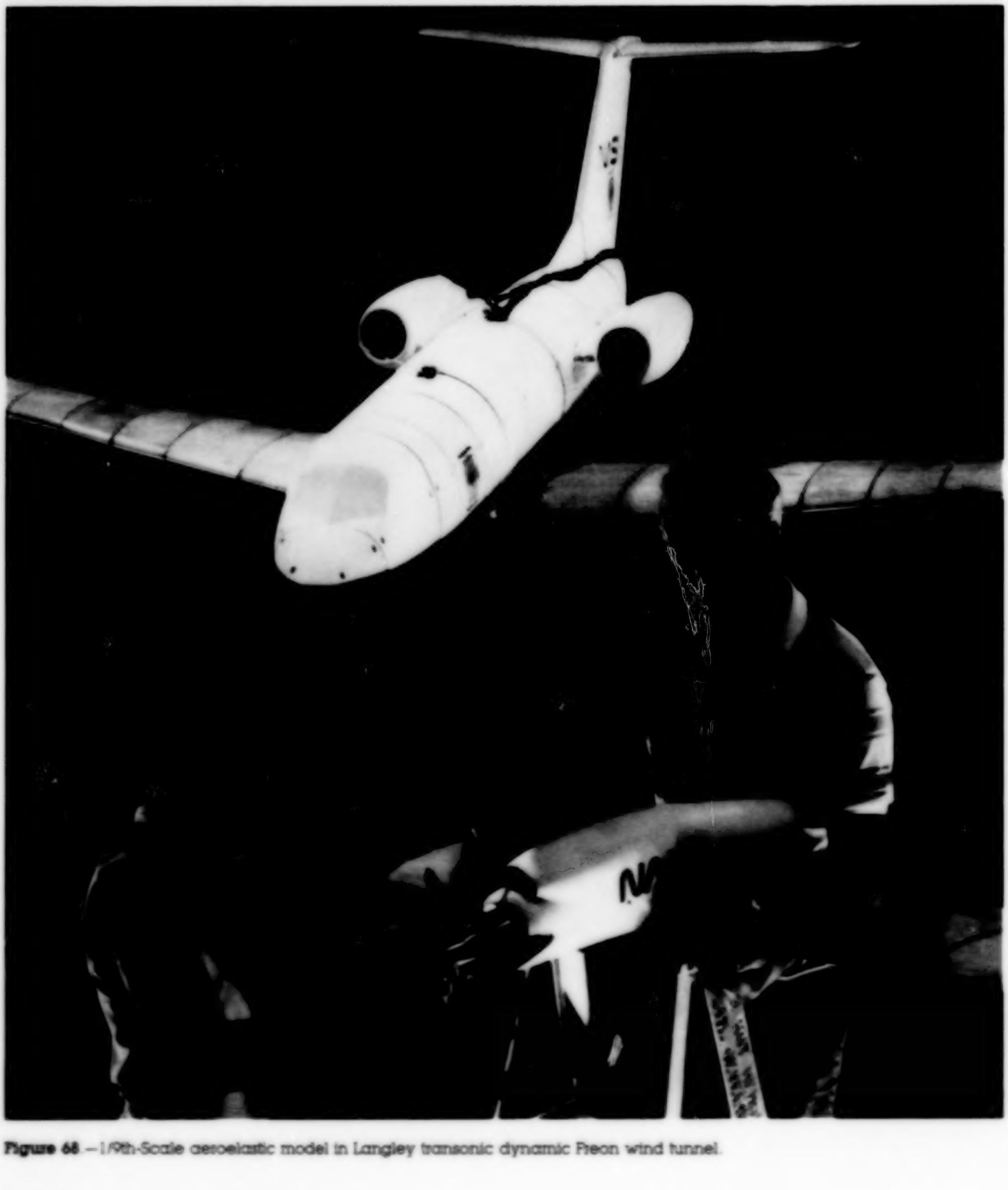


Figure 68.—1/9th-Scale aeroelastic model in Langley transonic dynamic Freon wind tunnel.

A second 1/9th-scale model aircraft was tested for stability and control in two Langley 16-foot transonic wind tunnels in late 1985 and 1986 (fig. 69). High-speed testing was first conducted in the 16-foot transonic tunnel, and then low-speed tests were performed in the 4-meter tunnel. In both test series an unmodified Gulfstream II model was first used to establish baseline characteristics, and then the modified PTA aircraft model was tested both with and without propfans to establish performance, stability and control, and handling characteristics for the planned flight test envelope. Results from both Langley tunnels confirmed that the PTA aircraft would be capable of safely testing the propfan over the entire flight test envelope. Drag increments were recorded for comparison with later flight data. Stability and control test results for the models exhibited acceptable force and moment characteristics for all configurations. In addition, these tests showed that the airflow into the left-side Spey turbofan flow-through nacelle was acceptable with the propfan installed.

The 1/9th-scale stability and control model was modified to a semispan configuration for a propfan-plane flow survey test. This test was performed in January 1987 in the Lewis transonic wind tunnel. Data were recorded from Mach 0.4 to 0.86 and for nacelle tilts of −3°, −1°, and 2°. Overall, the wind tunnel tests verified the predicted operating characteristics and confirmed that flight testing could be safely conducted as planned.

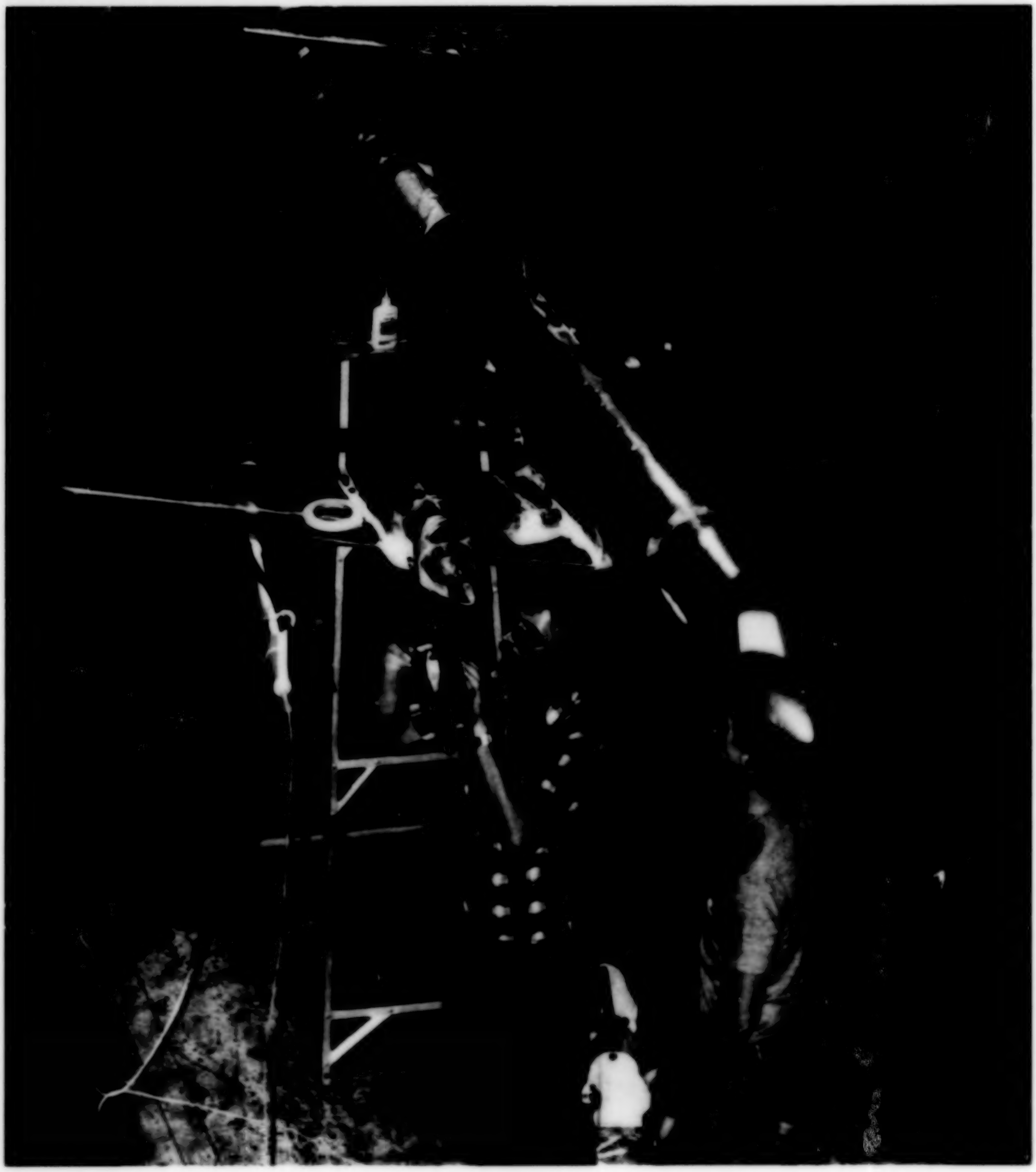


Figure 69.—1/9th-Scale stability and control model in Langley 16-foot transonic wind tunnel.

PTA Ground Static Tests

The engine gearbox, forward nacelle, and propfan assembly was shipped to Chula Vista, California, for functional checkout testing at Rohr's Brown Field static test stand (fig. 70). The test objectives were to confirm propulsion system operability, to substantiate propfan structural integrity, and to determine acoustic characteristics before proceeding with the flight test program.

Testing took place in May and June 1986. Over 50 hours of testing was completed at loads to 5300 shaft horsepower and speeds to 105 percent of propfan design. All test objectives were met: the propulsion system functioned according to design, all control systems operated satisfactorily, and the flight instrumentation system operated as planned. Propfan blade stresses and propulsion system temperatures, pressures, and vibrations were within specified limits, and specific fuel consumption was better than expected. The static tests successfully cleared the propulsion system for the flight tests.

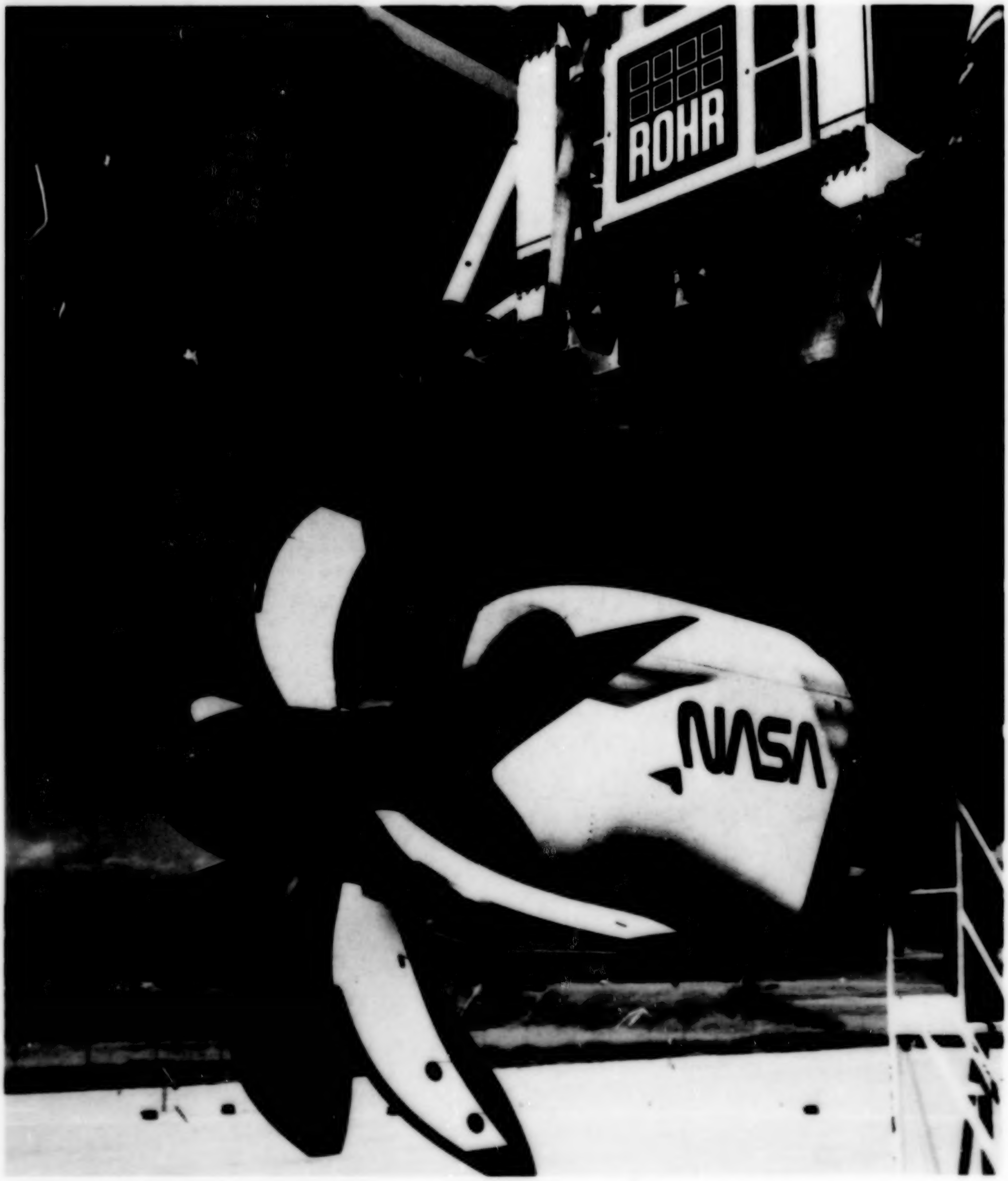


Figure 70.—PTA propfan installed at Rohr's Brown Field static test stand.

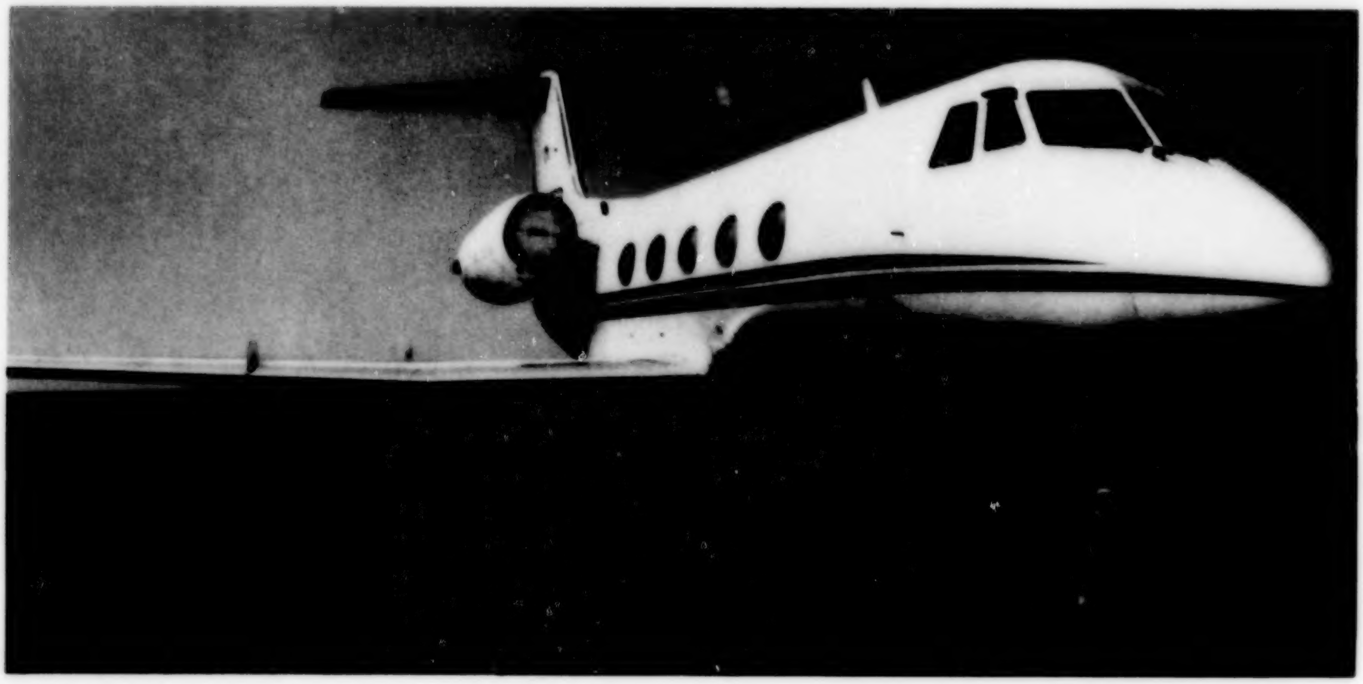


Figure 71.—Gulfstream II acquired for flight testing.

Flight Tests

In July 1986 the assembly was removed from the Rohr test stand, cleaned, inspected, and separated into its major components for shipping. The propfan was shipped to Hamilton Standard for refurbishing, and the remaining hardware was shipped to Gulfstream in Savannah, Georgia, for installation on the Gulfstream II aircraft.

In preparation for flight testing a Gulfstream II aircraft (fig. 71) was obtained in May 1986 and modified to the PTA configuration. The work was performed at Gulfstream in accordance with Lockheed designs. For this modification the skin and structure of the left wing were strengthened (fig. 72) to accommodate the weight of the propfan propulsion system, and the right wing was modified to support the over-2000-pound static counterbalance boom.

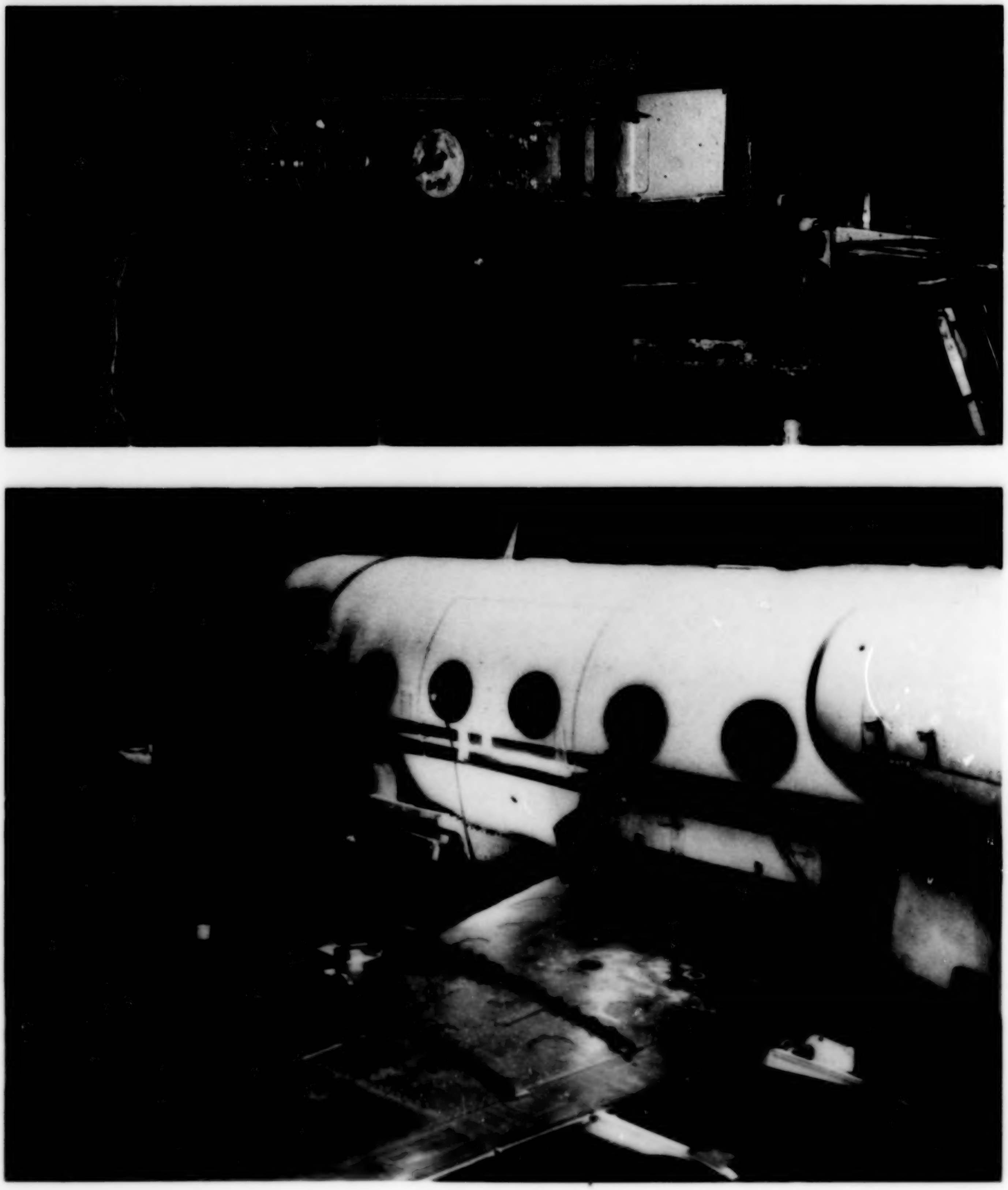


Figure 72.—Structural modifications to Gulfstream II. (a) Wing structural beef-up. (b) Beefed-up wing joined to fuselage.

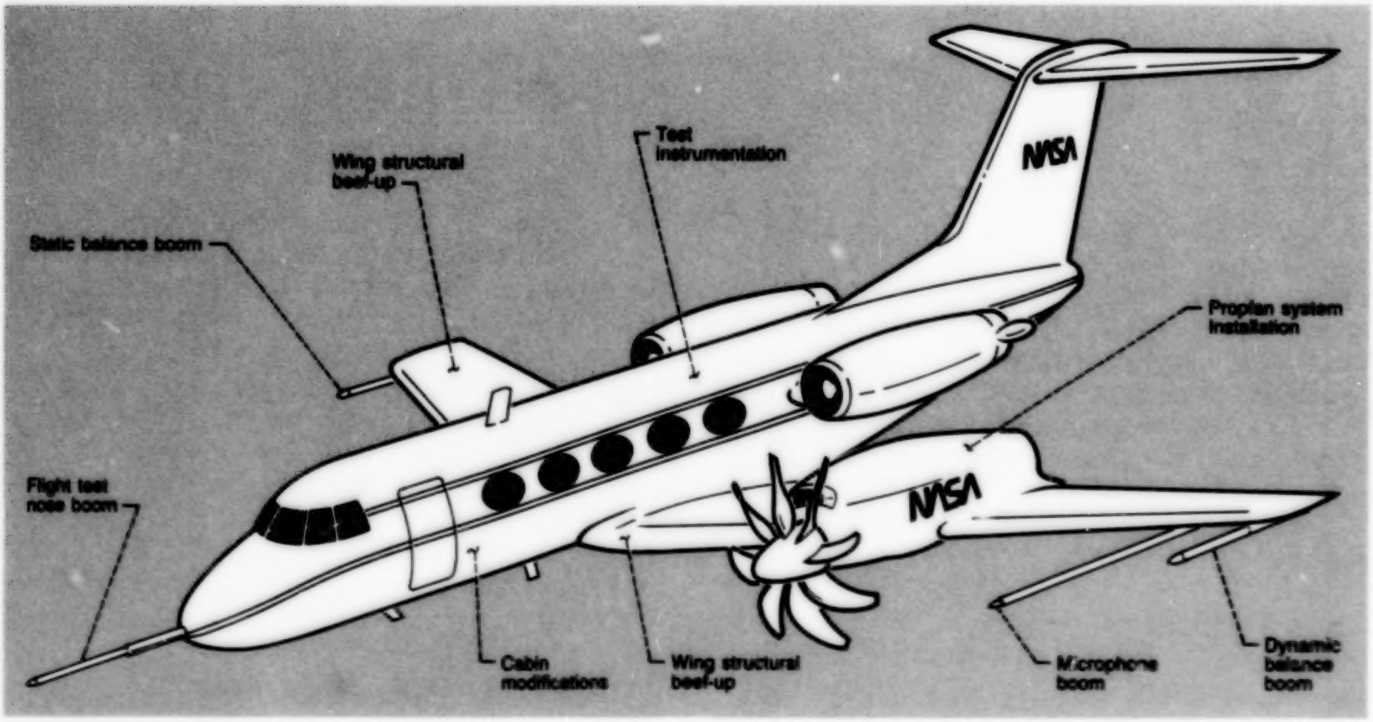

Test instrumentation
Wing structural beef-up
Static balance boom
NASA
Propfan system installation
Flight test nose boom
NASA
Cabin modifications
Wing structural beef-up
Microphone boom
Dynamic balance boom

Figure 73.—Modified Gulfstream II PTA aircraft.

More than 600 sensors were added to the aircraft and the propulsion system to monitor stress, vibration, acoustics, surface pressure, and temperature. Fuel, hydraulic, electric, compressor bleed air, and instrumentation lines were routed through the wing to the PTA nacelle, and the wing flaps were strengthened to prevent acoustic fatigue. A microphone boom for measuring free-field noise was installed on the left wing outboard of the propfan at a distance equal to the fuselage distance from the propfan. A nose boom was also added to measure aircraft speed, angle of attack, and yaw angle. Instrument consoles for monitoring and recording data during testing were also installed in the fuselage. All the installations and modifications shown in figure 73 were completed by February 1987.

Before flight testing could begin, Lewis with the support of Langley and Dryden thoroughly reviewed all aspects of aircraft airworthiness. The NASA Airworthiness Committee's concerns were satisfied and in early March the PTA flight test program began.

The PTA flight test was designed to verify the structural integrity of the propfan and to obtain propfan noise (near field, far field, and aircraft interior) and vibration characteristics. Flight tests to evaluate the effectiveness of an advanced cabin acoustic treatment are planned for early 1988. The results will be compared with predictions and model test results to verify codes and to provide a baseline for industry use in future commercial applications.

Throughout the flight tests propfan blade stresses were monitored by 30 strain gages to verify safe operation. All data, such as engine rotational speed and torque, blade angle, fuel flow, and vibrations, were recorded by onboard recorders. Critical flight safety data were simultaneously telemetered to a ground data center. Near-field noise was measured by microphones on the exterior of the fuselage, on the wing and the wing microphone boom, and inside the aircraft cabin.

Static pressure measurements in the nacelle-wing area were recorded to predict the flowfield at the propfan. These flow conditions were computed by Lockheed's QUADPAN code with corrections based on model flowfield data. They were used as input to the Hamilton Standard blade stress prediction code. The calculated blade stress will then be compared with the measured stress to validate the stress prediction code. In addition, accelerometers located on the wing and fuselage structure as well as on the propfan propulsion system provided data for assessing structure-borne noise.

The flight program was planned to gradually expand the operating envelope. First, aircraft operating characteristics were verified by flying the Gulfstream II with the propfan blades removed. Operating characteristics with power were then established with the blades installed. Ground and taxi tests began at Gulfstream's Savannah plant on March 5, 1987. The first flight, without the propfan blades, was on March 6. Handling characteristics were good and the aircraft was ferried from Savannah to Lockheed's Marietta, Georgia, plant on March 13 for further prop-off checkout flights. These flights were successful in that the performance, stability and control, and aircraft handling were as predicted from the model wind tunnel tests.

In early April the modified Gulfstream II was equipped with the propfan blades as shown in figure 74. The first flight with the propfan blades installed and functioning occurred on April 29, 1987. The PTA propfan was successfully air started at altitudes of 5000 and 6000 feet and flown to 230 knots at 10,000 feet. Since then the aircraft has operated at speeds to Mach 0.89 in airworthiness testing at 28,000 feet without any evidence of airframe or propfan flutter.

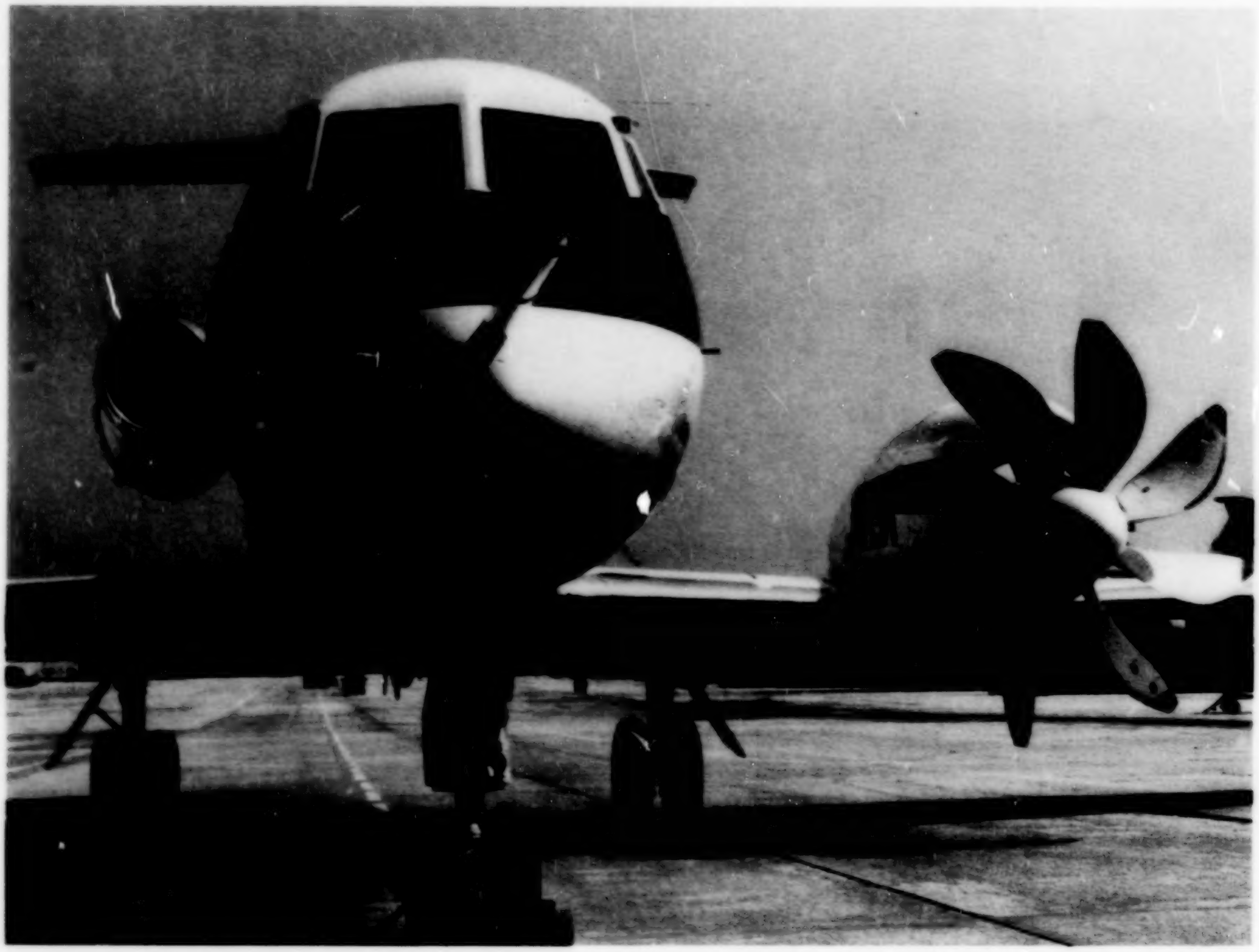


Figure 74.—PTA aircraft with propfan blades installed.

High-speed Mach buffet was observed above Mach 0.8 during airworthiness testing as the result of flow separation and reversal problems in the aft nacelle–wing trailing-edge region. These problems were solved by adding vortex generators at strategic locations on the wing and nacelle surfaces to energize the flow and by extending the tailpipe aft into the spill shield. As a result the PTA Gulfstream II was cleared for research flight testing to Mach 0.85 in level flight at 28,000 to 40,000 feet. Aircraft stability and control and handling characteristics were good, and propfan blade stresses were acceptable at all flight conditions. The PTA Gulfstream II in level flight is shown in figure 75.

High-altitude research testing began on July 6, 1987, and was completed on September 9, 1987. Propfan stresses, source noise, aircraft interior noise, and aircraft vibrations were measured at altitudes from 5000 to 35,000 feet with Mach numbers ranging from 0.4 to 0.85. Propfan rotational speeds were set at 75 to 105 percent of design corrected rotational speed at four power loadings. Data were obtained at three nacelle tilt angles, $-3°$, $-1°$, and $2°$, to determine the effects of inflow angle on blade stress and noise. Over 600 data parameters were recorded for 500 flight conditions. Blade stresses were at all times well within the limits specified by Hamilton Standard for infinite blade life.

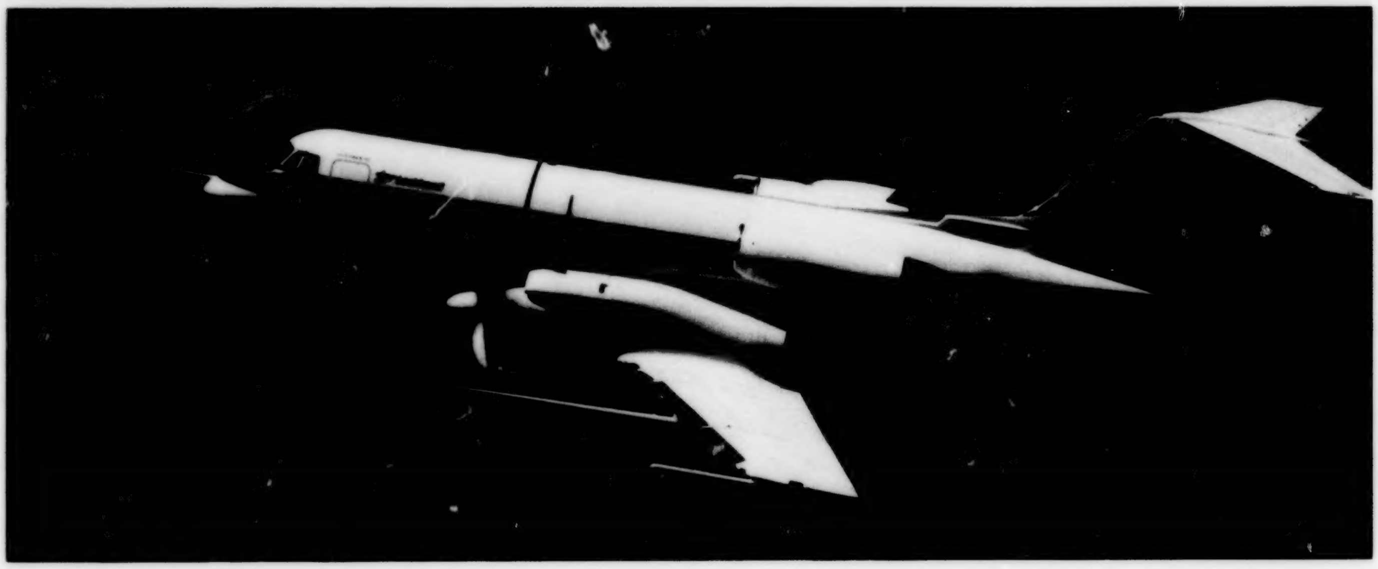


Figure 75.—PTA aircraft during flight tests.

Upon completion of the high-altitude performance testing, the aircraft was flown to the NASA Wallops Flight Facility in Virginia for low-altitude noise testing. Propfan source noise was measured with aircraft microphones, and far-field noise was measured with ground-based microphones. These measurements were made at an aircraft speed of 190 knots at altitudes from 850 to 1600 feet. Data were obtained at more than 50 flight conditions over a range of propfan tip speeds and power settings and at three nacelle tilt angles. For a baseline comparison acoustic data were also obtained with the propfan blades removed.

High-altitude enroute noise data were obtained in late October and early November 1987 in cooperation with the Federal Aviation Administration. The NASA Learjet mapped the source noise pattern directly below the Gulfstream II propfan in flight for comparison with data recorded on an array of FAA ground microphones. This testing was performed to validate an FAA atmospheric attenuation model and to obtain a representative matrix of propfan enroute ground noise data.

The forced-vibration response and acoustic data from the single-rotating PTA tests have led to a clearer understanding of the similar, but more complex, interactions encountered in counterrotating engine systems, such as those being demonstrated on the Boeing 727 and McDonnell Douglas MD–80 aircraft. The basic modeling codes when fully developed became the foundation for the codes needed to design counterrotating blade rows.

Counterrotating Turboprops

Researchers at Ames had determined that some of the swirl produced by wing-mounted, tractor, single-rotating propfans could be removed with stators, or to a lesser degree with contoured wings. Essentially all the swirl, however, could be removed by a counterrotating propfan, which would recover swirl directly in the aft blade row and offer twice the power of a single-rotating system for the same overall tip diameter—particularly important for larger aircraft, which require higher power.

The counterrotating propfan also would not be accompanied by the weight and drag penalties associated with stators. A gain of 6 to 8 percentage points in propulsive efficiency—a substantial performance payoff—is possible if all the swirl is recovered from the propeller wake. This is approximately equal to a block fuel saving of 5 percent. As figure 76 shows, this benefit has been demonstrated in scale-model tests of single- and counterrotating propfans.

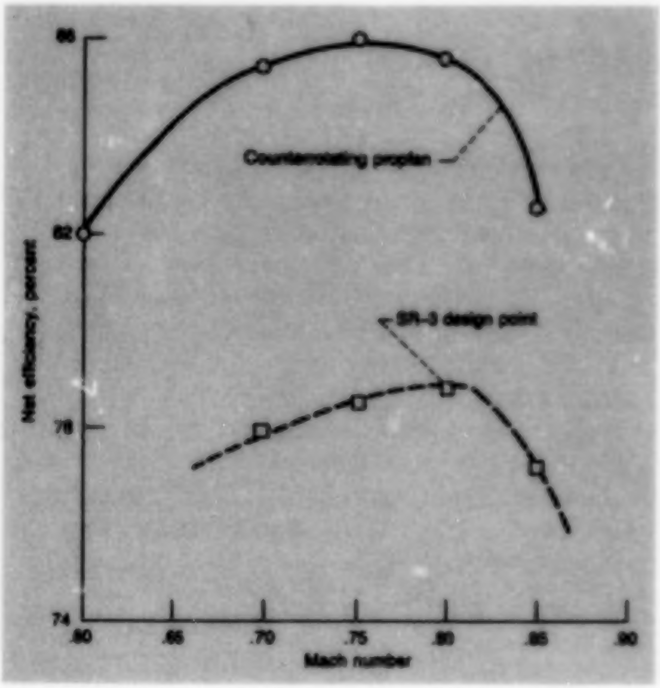


Figure 76.—Variation of net efficiency with Mach number.

Also with the counterrotating propfan, aft-mount pusher installations are attractive from an aircraft interior noise standpoint, allow a cleaner, more uncluttered wing, and may improve lift–drag characteristics. Single-rotating pusher propfans are not attractive because they lack the potential for swirl recovery and require a longer strut for their larger diameter propellers.

With the incentive afforded by fuel economy and by the greater power for a given size, the counterrotating propfan is an attractive propulsion system for commercial aircraft. However, the technical challenges of aerodynamic interaction between blade rows, aeromechanical stability, and acoustics had to be investigated before the concept could be understood well enough to design a demonstrator engine.

Model Tests

NASA's approach to these technical challenges was to study counterrotating propfans on test rigs mounted in wind tunnels. In 1983 NASA began the process of designing and fabricating rigs to test 2-foot-diameter counterrotating propfans. The rigs were designed to enable testing of both tractor and pusher configurations simulating either wing- or aft-fuselage-mount installations. NASA let major contracts with Hamilton Standard and General Electric for the design and fabrication of several counterrotating propfan models and their evaluation in wind tunnels and acoustic facilities at Hamilton Standard, UTRC, Boeing, General Electric, and NASA.

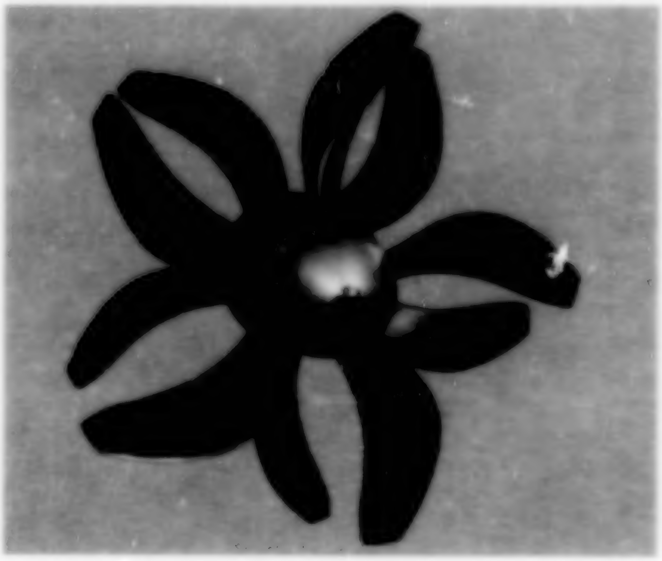


Figure 77.—Model of CRP-X1 five- by five-blade counterrotating propfan.

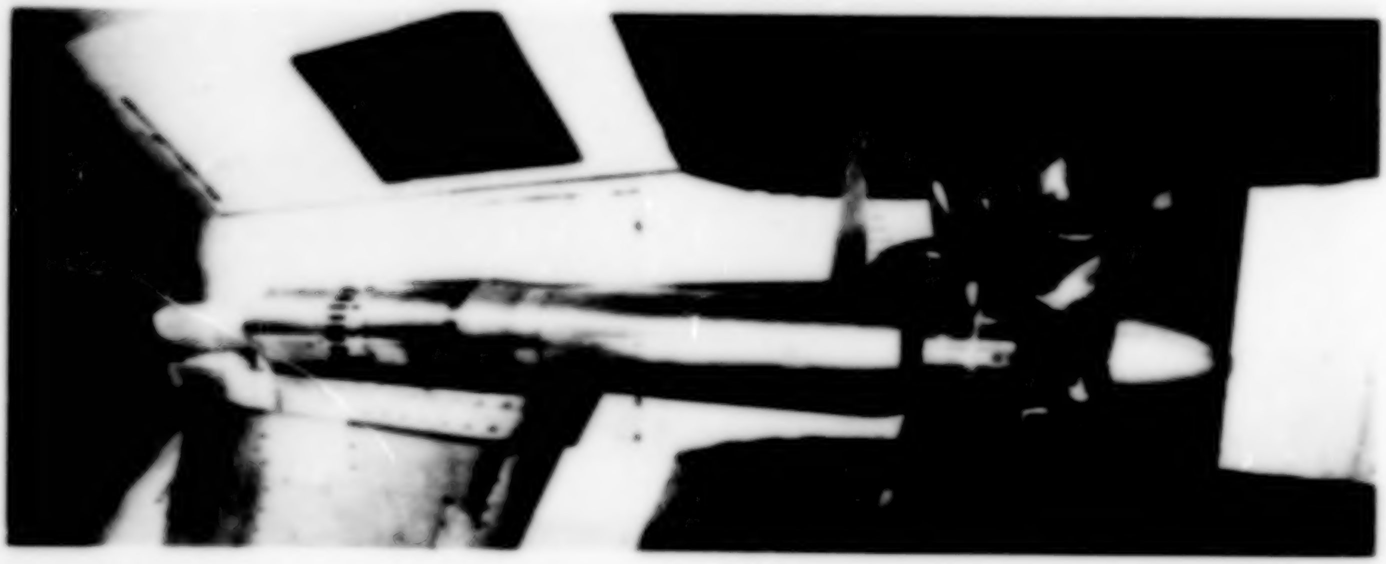


Figure 78.—CRP-X1 model in United Technologies Research Center's high-speed tunnel.

Hamilton Standard Counterrotation Tests

A counterrotating model, CRP-X1, typical of a geared tractor propfan system (fig. 77) was tested from Mach 0.2 to 0.85 at tip speeds to 750 feet per second in UTRC's high-speed 8- by 8-foot wind tunnel (fig. 78). During testing, which took place between April 1985 and March 1986, data were recorded on aerodynamic performance, structural integrity, and aeromechanical stability. No structural or aeromechanical problems were found. The aerodynamic efficiency was 86 percent at Mach 0.75, about 8 percentage points better than that for the equivalent SR-3 single-rotating propfan. Some of the test results are shown in figure 79.

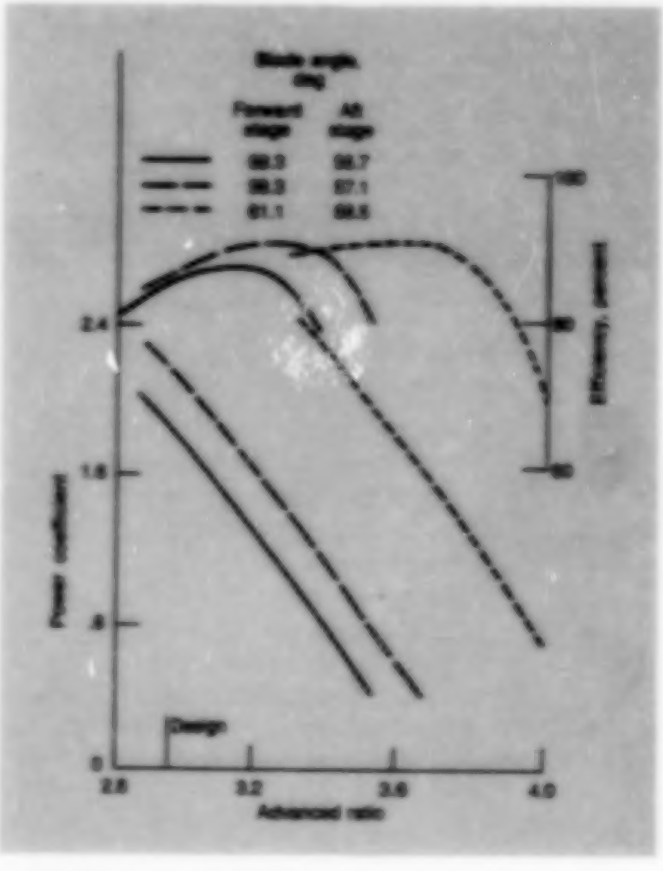


Figure 79.—Results of CRP-X1 high-speed wind tunnel tests.

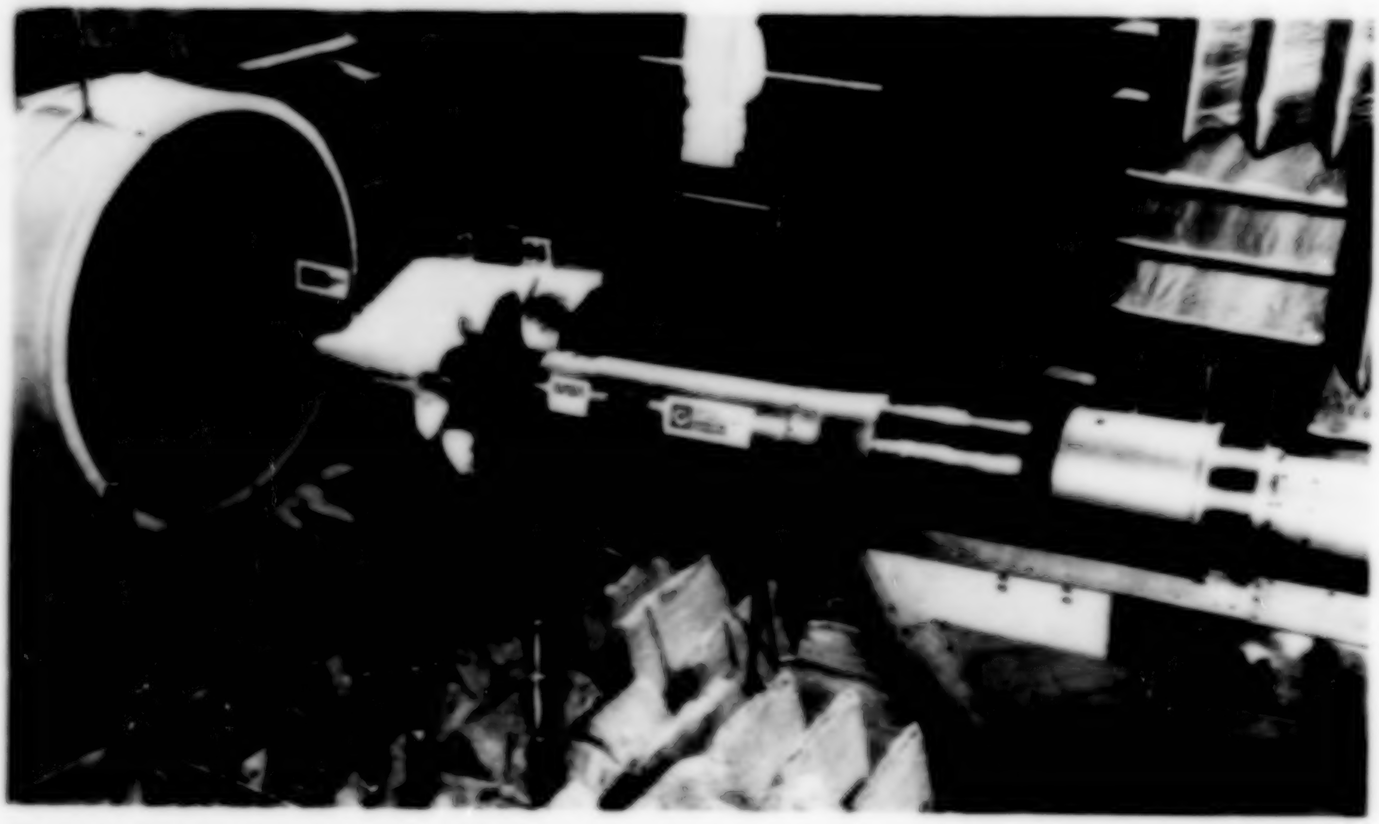


Figure 80.—CRP-X1 model in United Technologies Research Center's low-speed acoustic research tunnel.

Following the high-speed tests the CRP-X1 was installed in the UTRC low-speed acoustic research tunnel (fig. 80), and tests were run from April through June 1986 on both pusher and tractor configurations. Flow Mach numbers to 0.26 and flow inlet angles to 4° were tested. Because the second and third blade passing frequencies were higher than expected, the tractor was 5 decibels noisier than predicted from single-rotating data. Although the pusher was 2.4 decibels noisier than the tractor configuration at 0° angle of attack, the noise difference virtually disappeared at 4°. The noise of the pusher configuration was insensitive to the spacing between blade rows and between the pylon and the forward-stage blade row.

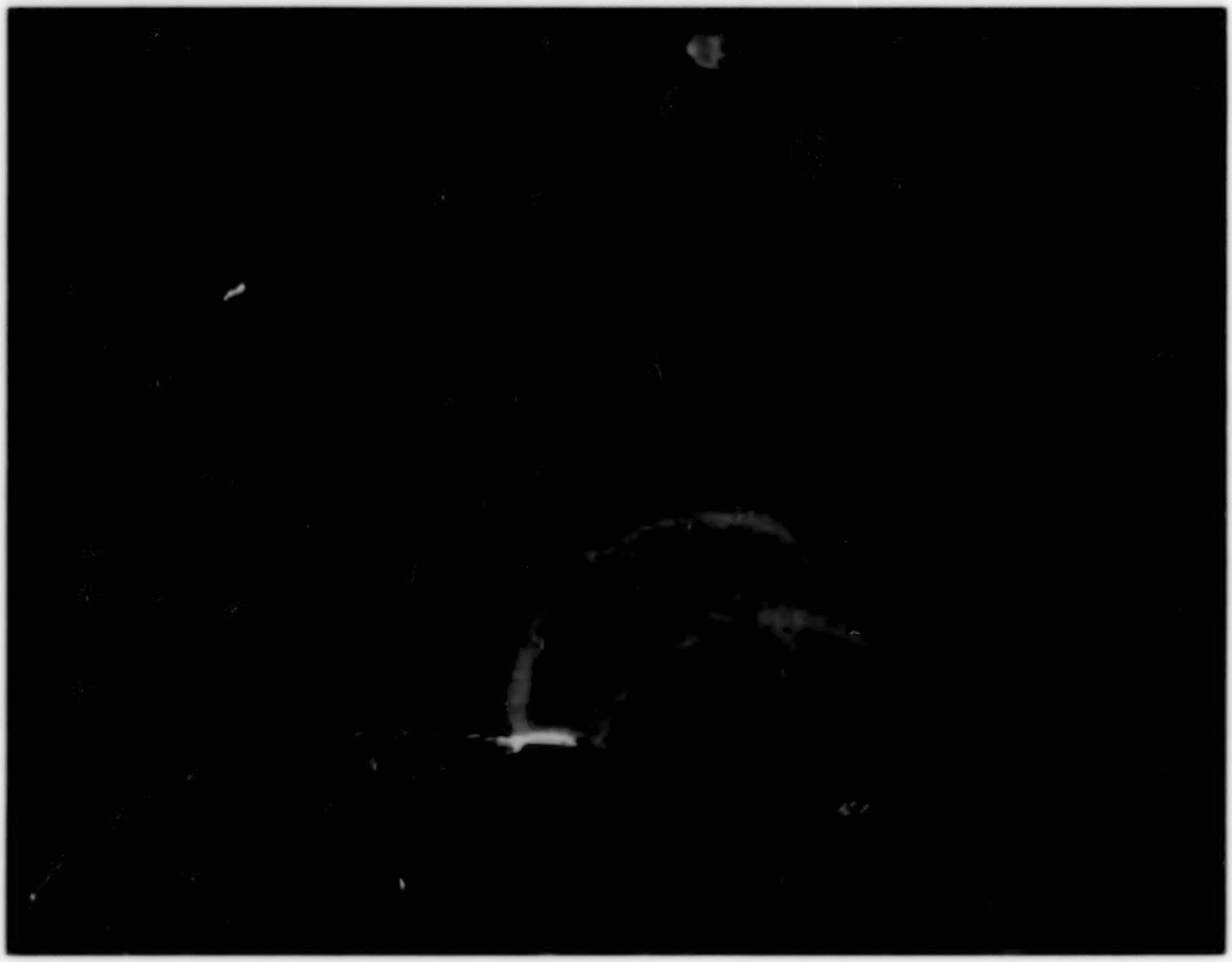


Figure 81.—Leading-edge vortex solution for aft stage of CRP–X1 model.

Hamilton Standard and Lewis engineers are using the CRP–X1 model to develop a flow visualization method based on a three-dimensional Euler solution and a high-resolution grid. The leading-edge vortices and flow streamlines computed at Mach 0.2 are shown in figure 81. Oil patterns observed during low-speed tests in the UTRC facility correlated closely with the analytical results.

General Electric Counterrotation Tests

In 1983 General Electric designed and fabricated three similar counterrotating model test rigs. One of the rigs was used for low- and high-speed tests in Boeing's 9- by 9-foot low-speed wind tunnel and 8- by 12-foot transonic wind tunnel. The second rig was especially adapted for vertical operation in General Electric's cell 41 vertical anechoic chamber. The third rig was provided to NASA through a cost-sharing contract with General Electric to facilitate additional low- and high-speed testing in the Lewis 8- by 6-foot transonic wind tunnel and its 9- by 15-foot anechoic low-speed leg (fig. 82). The counterrotating model tests began at Boeing in May 1984, at General Electric in November 1984, and at NASA Lewis in July 1985. Aerodynamic, acoustic, and aeroelastic data were obtained for a variety of blade designs, speeds, and blade row spacings.

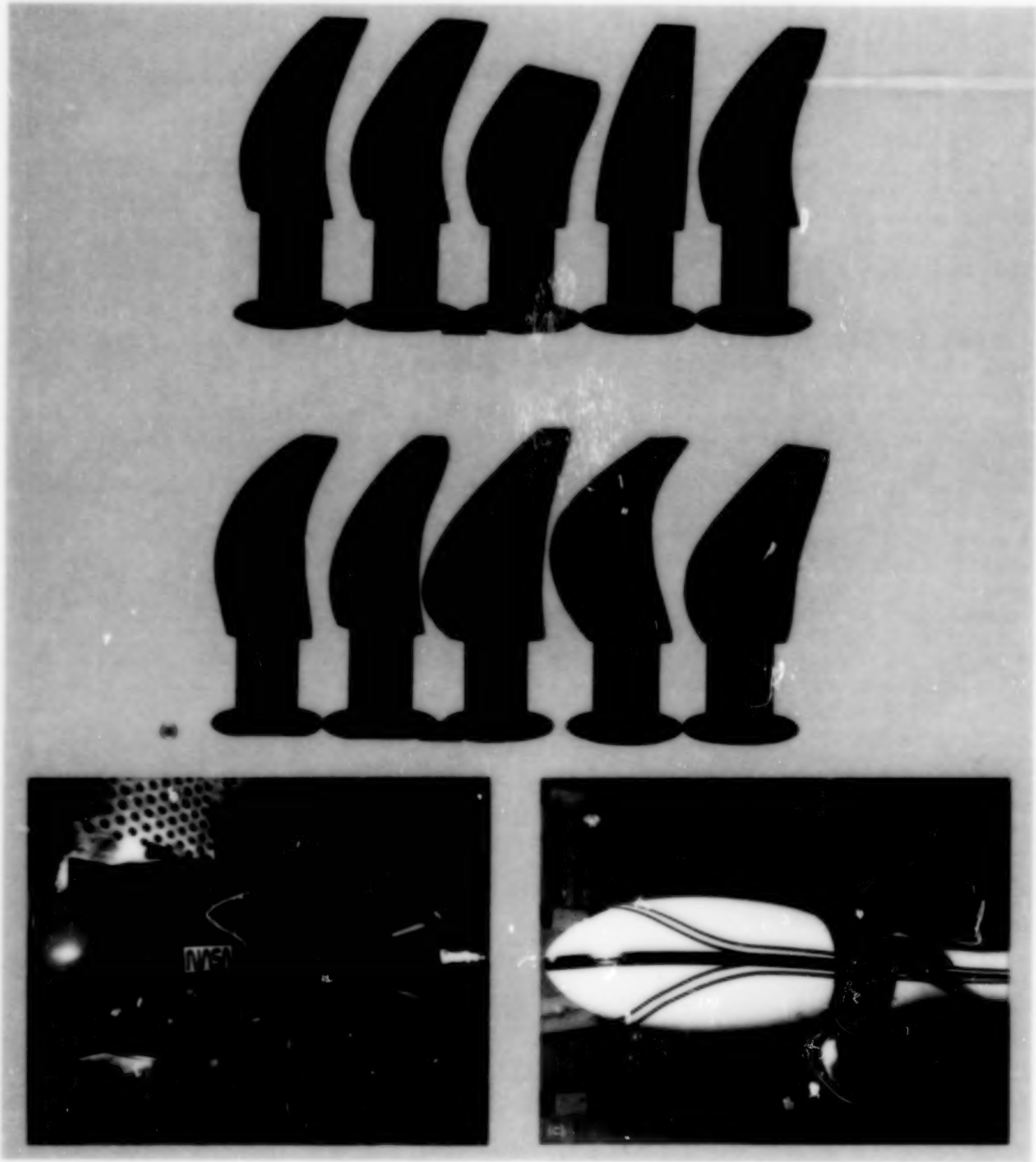


Figure 82.—Unducted-Fan (UDF) counterrotating models in Lewis wind tunnels.
(a) Model blade configurations. (b) Transonic wind tunnel. (c) Anechoic wind tunnel.

The blade efficiency was several points lower than predicted, possibly because of interaction between the blade rows. Also the results from the NASA tunnel and General Electric's anechoic chamber were 3 to 4 percentage points lower than results for the same model tested at Boeing. Tunnel recalibrations made in 1986 and 1987 resolved the differences, but the overall reduced performance is still being investigated.

Acoustic test results showed the counterrotating propfan to be only about 6 decibels noisier than a single-rotating propfan with equivalent tip speed and loading. However, additional tests have shown a number of effects that would reduce community noise from counterrotating turboprops. Increasing the spacing between blade rows and avoiding the acoustic reinforcement that occurs when the blade numbers match can reduce noise by 5 decibels (fig. 83). Reducing the diameter of the aft-stage blade row avoids interference with the tip vortex and reduces noise by several more decibels. Lowering the tip speed and reducing the blade loading can also bring about further reductions.

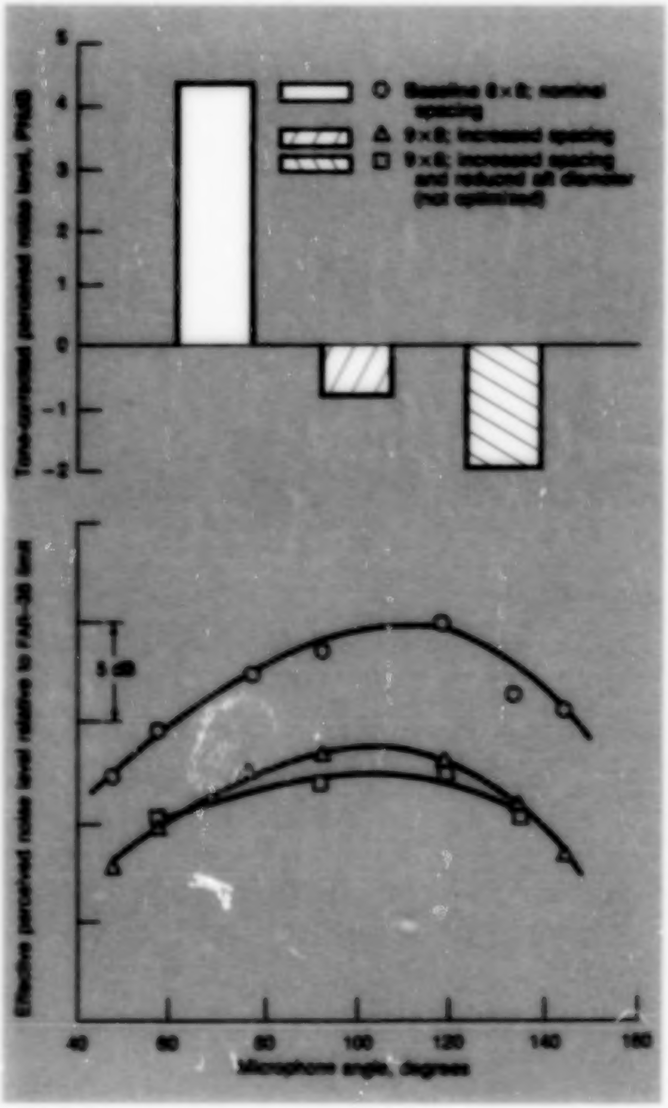


Figure 83.—Community noise from counterrotating propellers.

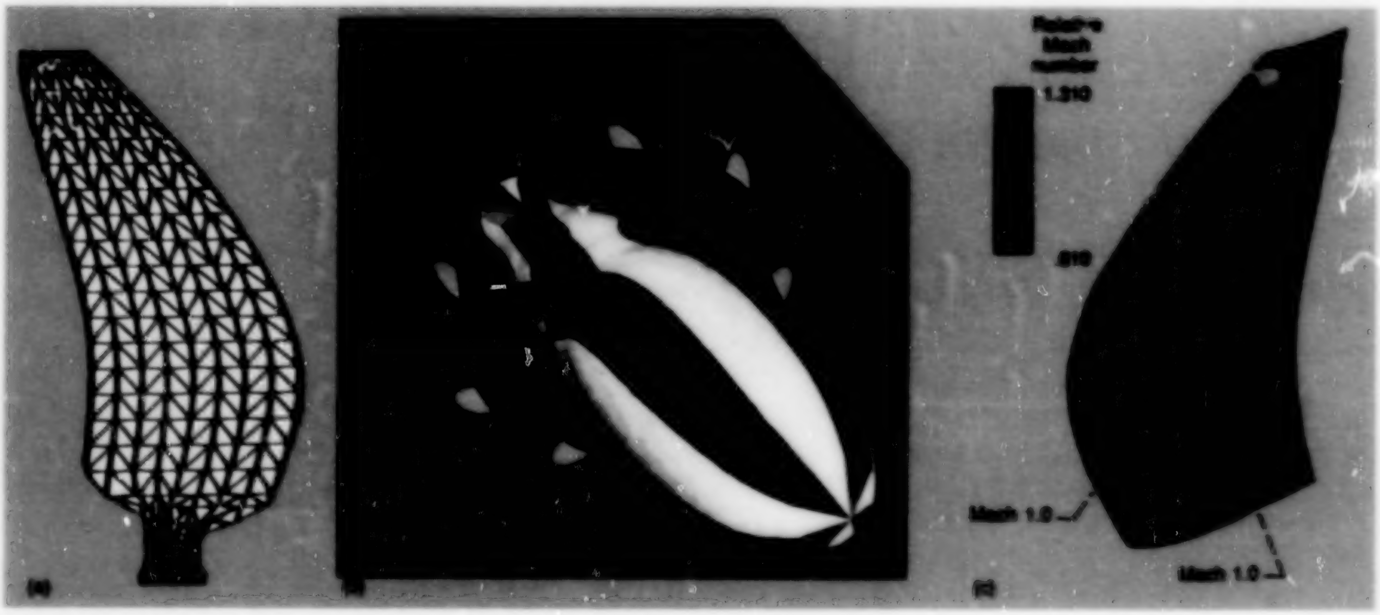


Figure 84.—Output of design codes for counterrotating blade rows. (a) ASTROP aeroelastic code. (b) Three-dimensional aerodynamic code. (c) Aeroacoustic prediction codes.

Design Code Development

The aerodynamic, aeroelastic, and acoustic design codes developed for single-rotating propfans formed the basis of the codes used for counterrotation analyses. Although the forward stage has a simple flowfield like the single-rotating propfans, there are interaction effects with the aft stage. To improve the prediction accuracy, the aft-stage inlet flowfield was adjusted to the forward-stage exit conditions. Figure 84 shows the results of various design codes that had been modified for counterrotating blade rows. The aeroelastic input included three-dimensional, unsteady aerodynamic effects for both subsonic and supersonic relative flows. The aerodynamic code is based on the three-dimensional unsteady Euler method and includes the effects of interaction between blade rows. The aeroacoustic prediction code uses a three-dimensional Euler solution for blade surface conditions to define the input to existing noise codes. As data become available from scale-model and full-scale tests, the codes will be improved to better represent the actual conditions. Lewis plans to continue testing scale-model propfans for continued code development.

Unducted Fan (UDF) Concept

By 1983 General Electric, convinced that the gearless, counterrotating Unducted Fan (UDF) engine (fig. 85) was a viable commercial concept, began to evaluate the feasibility of a commercial counterrotating turboprop engine that could power a 150-passenger aircraft. Rather than venturing into the uncertain area of gearbox design for a 20,000-shaft-horsepower engine, they proposed to directly drive the propfans with counterrotating turbine stages.

The projected specific fuel consumption at cruise for the UDF concept was 30 percent lower than that of the most modern turbofan engines being built, and about 50 percent lower than that of engines presently in use on 150-passenger aircraft.

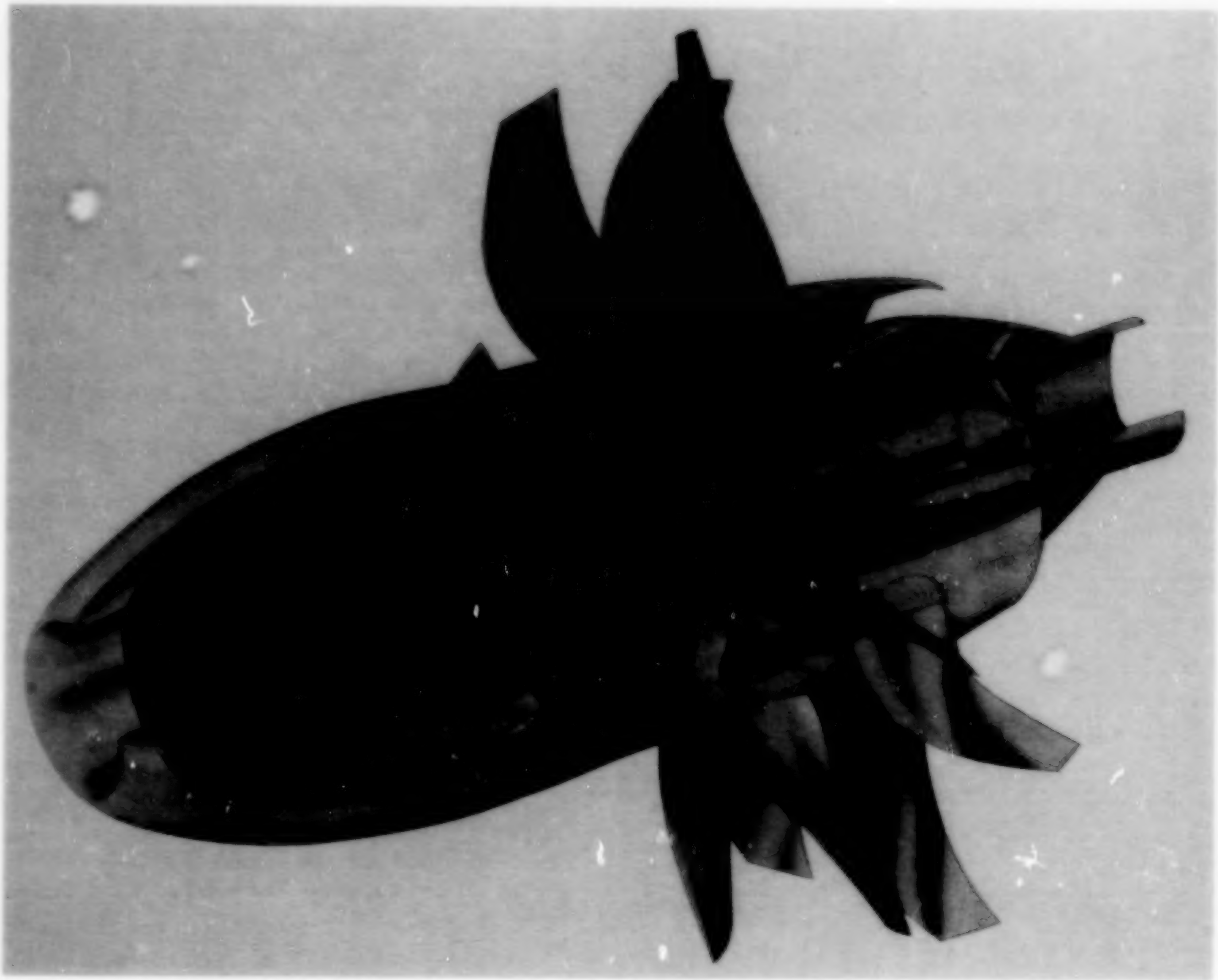


Figure 85.—NASA-General Electric Unducted Fan (UDF) engine.

NASA–General Electric UDF Design

In late 1983 General Electric approached NASA to see if the Government would be interested in participating in a technology demonstrator program for the UDF engine. The proposed proof-of-concept engine would use an existing F404 engine as a gas generator and would have the following design parameters:

Bypass ratio	32
Fan diameter, feet	11.7
Maximum nacelle diameter, feet	5.6
Overall pressure ratio	27
Fan pressure ratio	1.17
Thrust, pounds	25,000
Thrust-to-weight ratio (installed)	4.0
Specific fuel consumption at Mach 0.8, 35,000 feet, and maximum climb	0.52

After a thorough review NASA agreed to support the UDF proof-of-concept program through a contracted effort directed by Lewis. The contract began in early 1984 with the initial design and ground tests funded by NASA. This removed a great deal of the risk for General Electric and subtracted several years from the time that it would normally take the aircraft industry to develop a new fuel-efficient engine.

The objectives of the program were to show that the gearless propfan design worked and that its operation and control would be similar to those of existing turbofan engines. Data were to be obtained on the engine and its components during ground testing to allow projection of in-flight performance and to identify changes that would be needed if the concept became a commercial reality. Scale-model test results from single- and counterrotating rigs were used to support the full-scale blade design. The program structure is shown in figure 86.

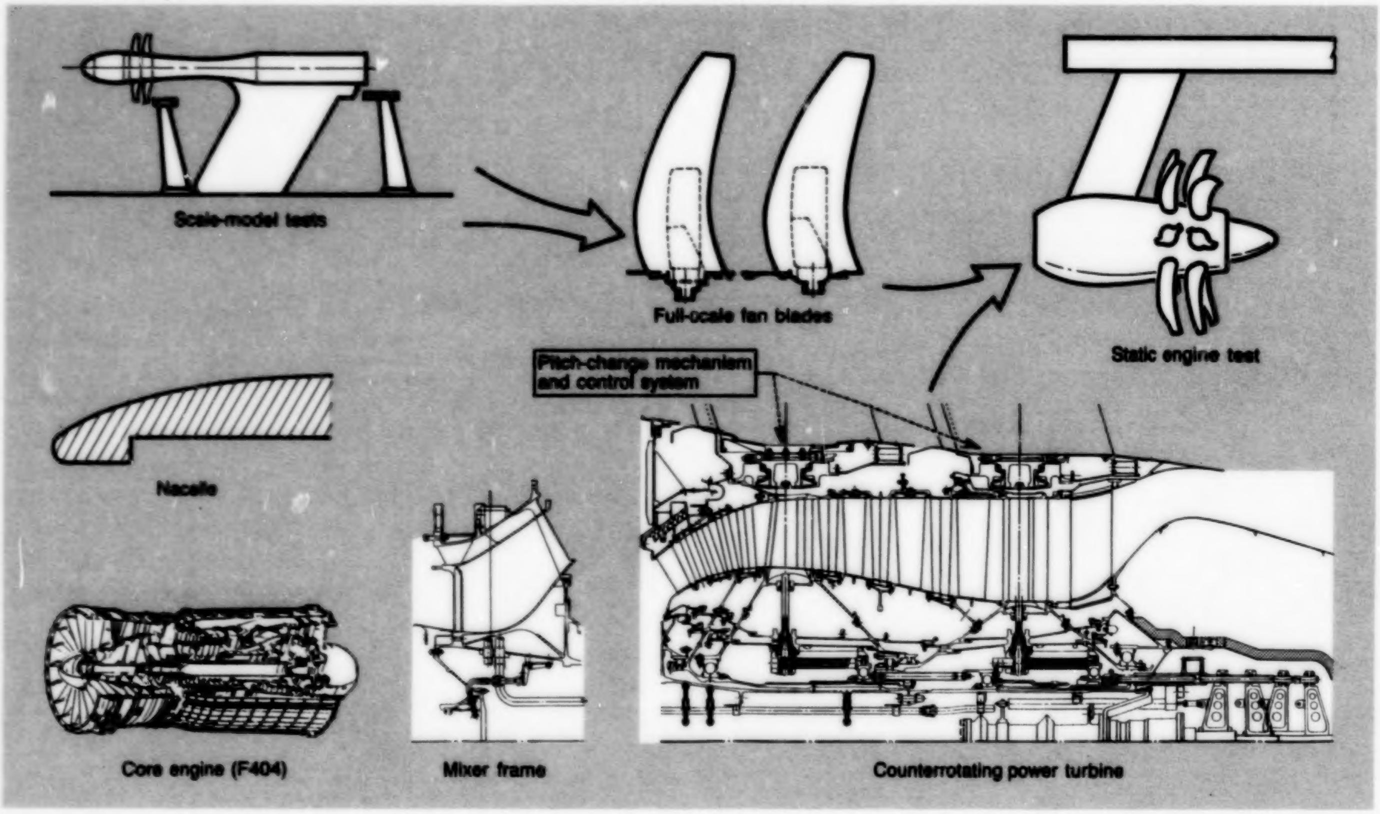

Scale-model tests
Full-scale fan blades
Static engine test
Pitch-change mechanism and control system
Nacelle
Core engine (F404)
Mixer frame
Counterrotating power turbine

Figure 86.—Elements of NASA–General Electric UDF Program.

To reduce costs by avoiding the expense of a special core engine, an F404 engine on loan to General Electric from the Government was chosen to supply power to the UDF propulsor. The F404 was coupled only aerodynamically to the propulsor (no shafts), as shown in figure 87, and had no research value other than to power the UDF propulsor. The components of primary interest were the counterrotating turbines, the pitch-change mechanism, the propfan blades, and the control system. The nacelle shape was determined by aerodynamic design codes and by scale-model tests at General Electric and NASA so as to provide the proper flowfield at the propfan plane. As shown in figure 88 the nacelle pressure contour was verified by flow tests with the scale-model counterrotating test rig. The tests and predictions were made for the unbladed and bladed conditions and compare well. The scale model is plotted in full size to show the model simulator nacelle shape relative to the full-size UDF.

Since the flowfield and the power requirements change with flight speed and altitude, the pitch-change mechanism and control system were designed to vary the propfan blade setting angle during operation and to provide setting angles for reverse thrust. Initial predictions of blade setting angle were made before the ground tests for comparison with the test results, and throughout the tests the systems were evaluated for smoothness and accuracy of operation.

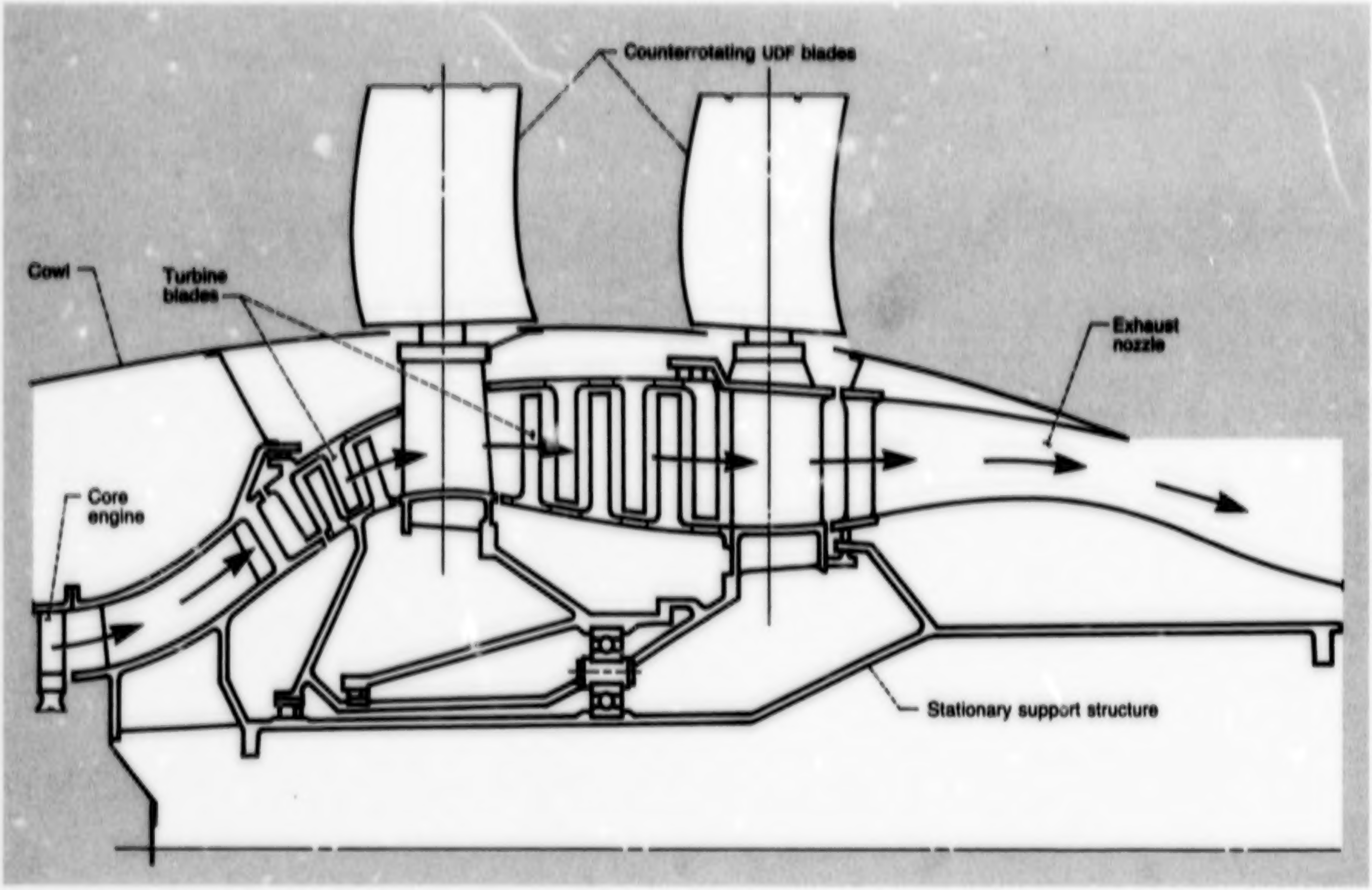

Counterrotating UDF blades
Cowl
Turbine blades
Exhaust nozzle
Core engine
Stationary support structure

Figure 87.—Schematic of UDF counterrotating propulsor.

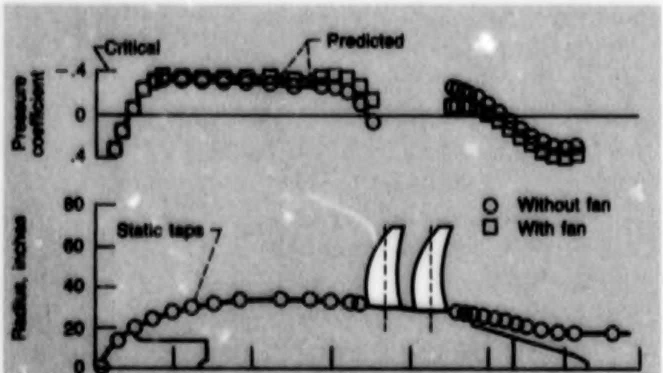


Figure 88.—Predicted and measured UDF nacelle pressure distribution.

The concept of using counterrotating turbines to drive the propfan blades directly was unique. Because of the low average wheel speed (218 feet per second) 12 stages (fig. 89) were needed to extract the required power. Six stages were cantilevered inward for ease of assembly, and all the blades were fabricated from sheet metal to save cost and weight. The blade dynamics and aerodynamic performance were not well defined, but the weight and size advantages for a counterrotating turbine were incentive enough to try the concept.

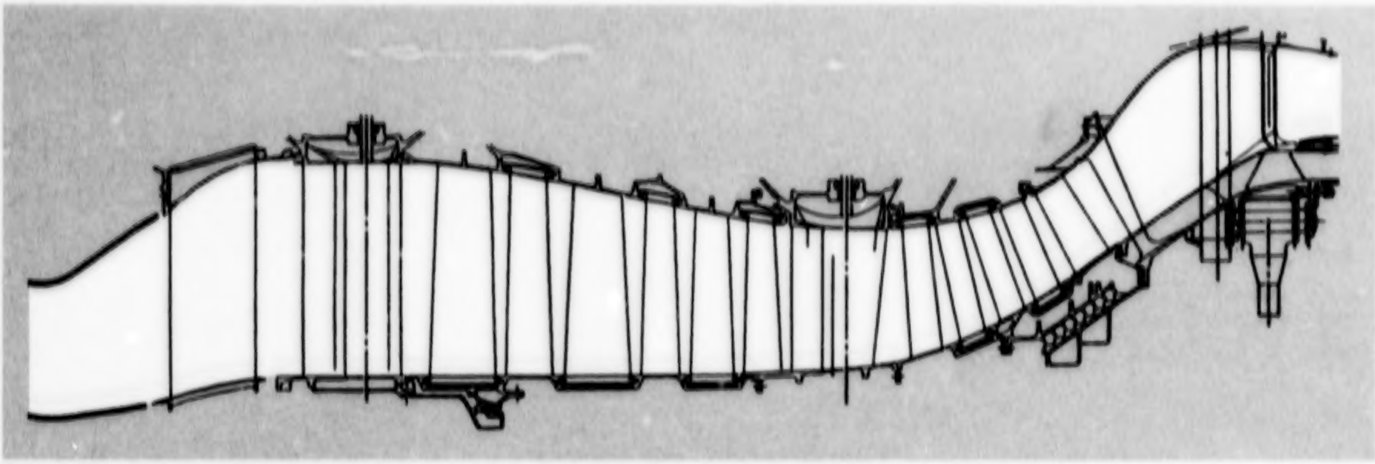


Figure 89.—Details of UDF counterrotating turbine. Average stage loading, $\Delta h/2U^2 = 1.15$ (where h is enthalpy in British thermal units per pound and U is average wheel speed).

During counterrotation rig testing at Lewis the blade set designed for Mach 0.72—called the F7–A7—had the highest efficiency, 82.5 percent at Mach 0.72, and 77.5 percent at Mach 0.8. Although blades designed specifically for Mach 0.8 would have somewhat higher efficiency at that speed, it was felt the proof-of-concept objectives could be demonstrated with the F7–A7 at a substantially lower cost than a new design for Mach 0.8. With this in mind a flow analysis of the F7–A7 was performed for a free-stream Mach number of 0.8 to see if the flow choked at the propfan blade hub. As figure 90 shows, there was one area in the second-stage hub with a streamline Mach number of 0.9—not high enough to have a large effect on blade performance.

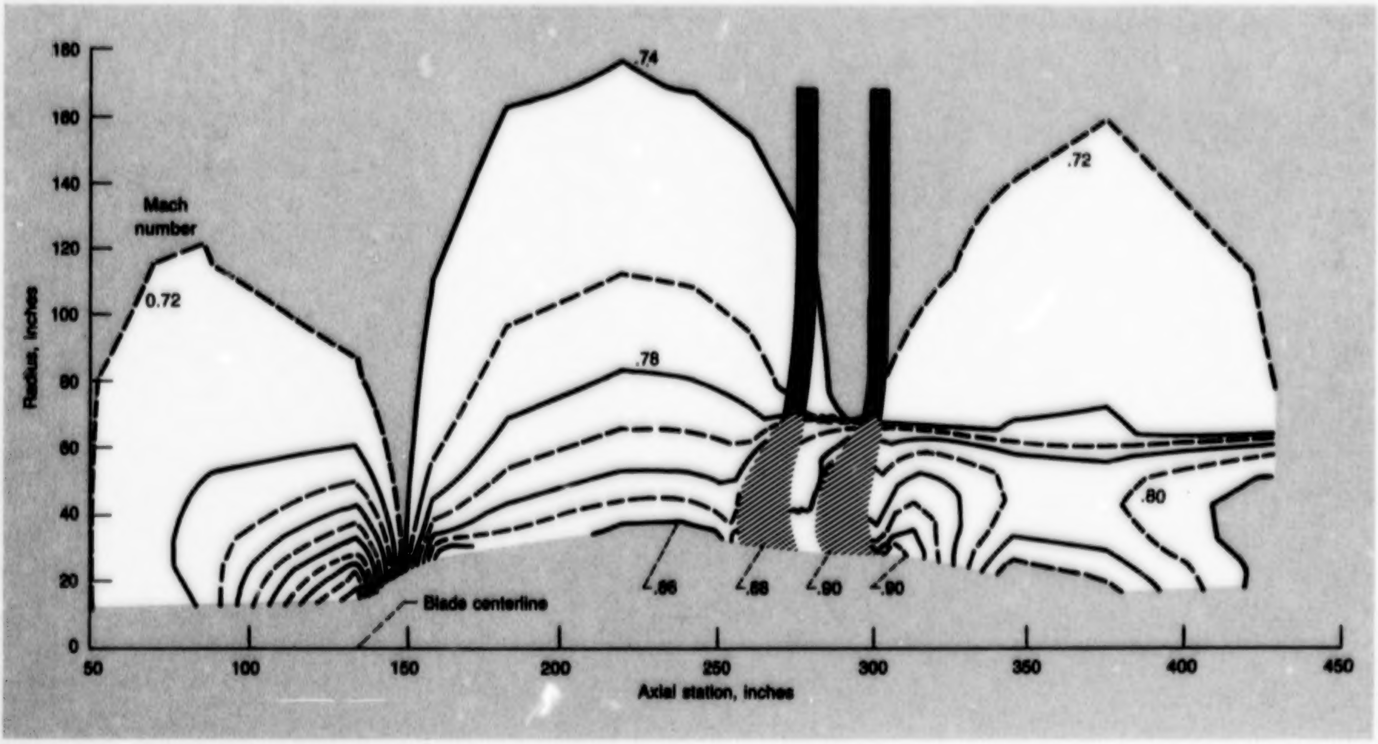
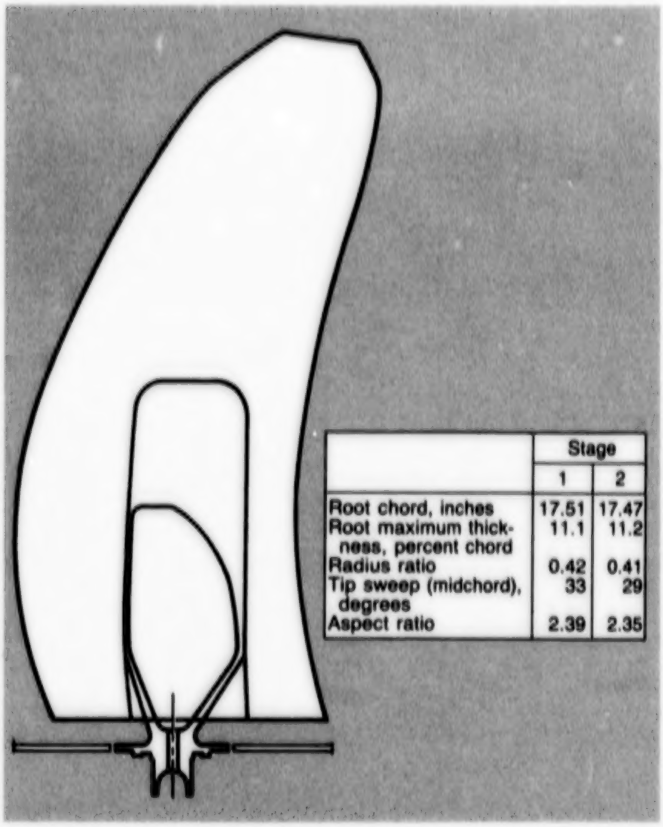


Figure 90.—Mach number distribution for F7–A7 counterrotating propfan at Mach 0.8 free-stream conditions.

The UDF blade design is somewhat different from the propeller type of construction used for the PTA blades. The PTA blade consisted of a full-length structural spar and a fiberglass shell; the shell of the UDF blade is the structural element and the spar is used for attachment. The UDF blade design and construction (fig. 91) are basically the same for both forward and aft blade rows. The blades have a titanium spar to about 50 percent span covered with graphite/epoxy plies. The plies are oriented in such a way as to tune the directional stiffness for blade shape control, strength, and aeromechanical stability. General Electric used NASA design codes for propeller ply design, flutter analysis, aerodynamic design, and noise generation and used model rig data to modify, improve, and verify their own in-house codes. The design of all the components, including the propfan blades, looked promising, but the real proof of concept would come when the engine was tested.



	Stage	
	1	2
Root chord, inches	17.51	17.47
Root maximum thickness, percent chord	11.1	11.2
Radius ratio	0.42	0.41
Tip sweep (midchord), degrees	33	29
Aspect ratio	2.39	2.35

Figure 91.—Mach 0.72 mechanical design of UDF propeller blade.

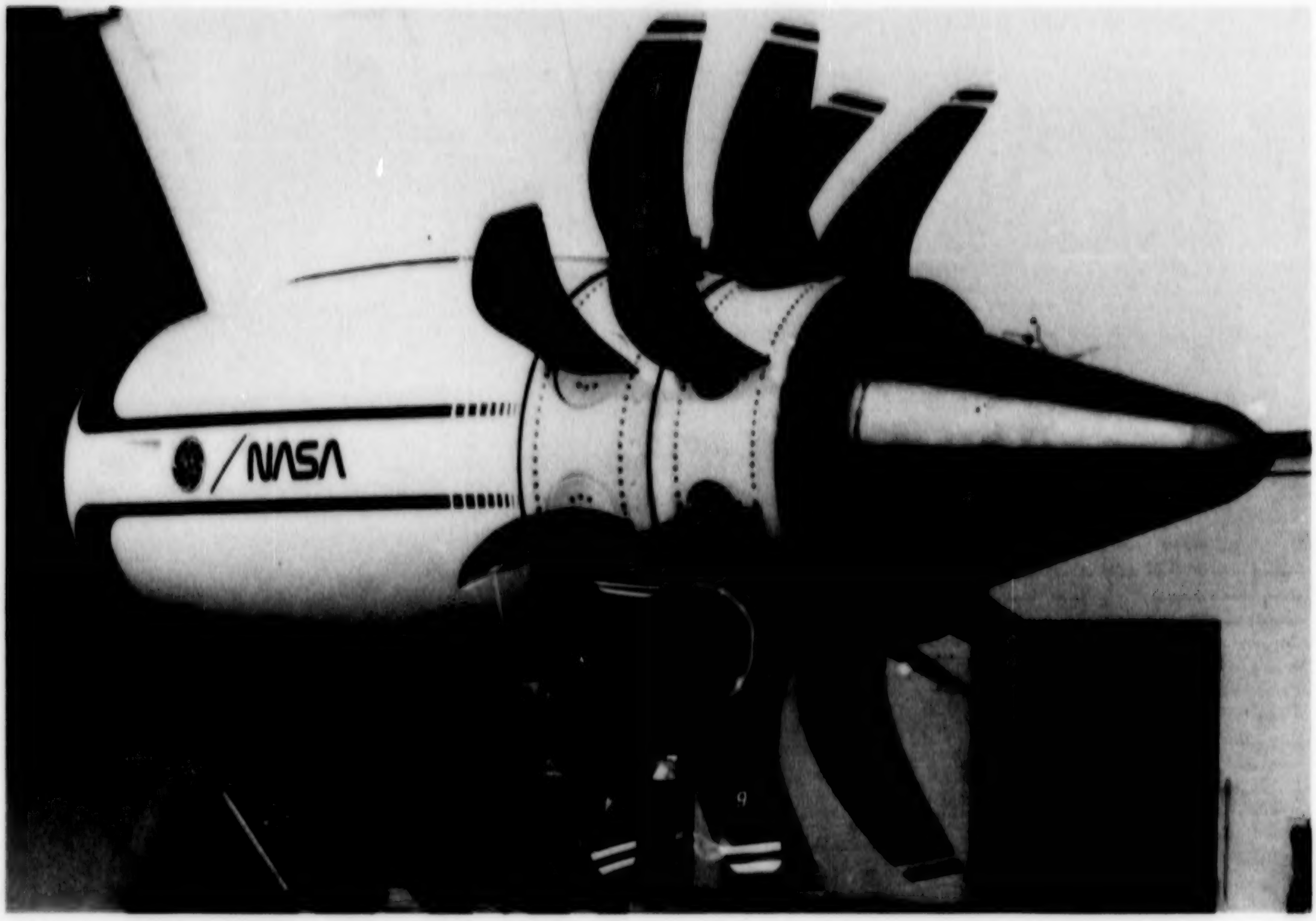


Figure 92.—Proof-of-concept UDF engine on test stand.

UDF Ground Tests

The UDF test program was begun in March 1985 at the General Electric test facility in Lynn, Massachusetts, with testing of the F404 core engine. The F404 gas generator is a military core and has larger blade clearances than a commercial engine. With an ideal generator the fuel consumption would be at least 5 percentage points lower. This engine had been modified by installing a variable-geometry stator row and by increasing the interstage bleed flow to provide the additional stall margin needed for matching the UDF propulsor requirements over the full range of engine operating conditions. These tests were completed in March, and the core engine was returned to General Electric's Evendale, Ohio, plant for assembly into the UDF engine. By August 1985 buildup and instrumentation were completed and the engine was installed on the test stand at Peebles, Ohio (fig. 92).

Testing started in late August and continued into October. In early October testing was interrupted to repair cracks at the joint between the cantilevered blades and the support rings in the counterrotating turbines. The blades were replaced, and damper pins were incorporated between adjacent blades to control the blade motion. At the same time the propfan blades were replaced because the graphite/epoxy shell tended to debond from the titanium spar. Later, during a high-power test (1350 rpm and 24,000 pounds corrected thrust) in February 1986 an aft-blade shell debonded, throwing the shell and cracking the spar. Although there was no other damage, researchers decided that it was time to strengthen the blades.

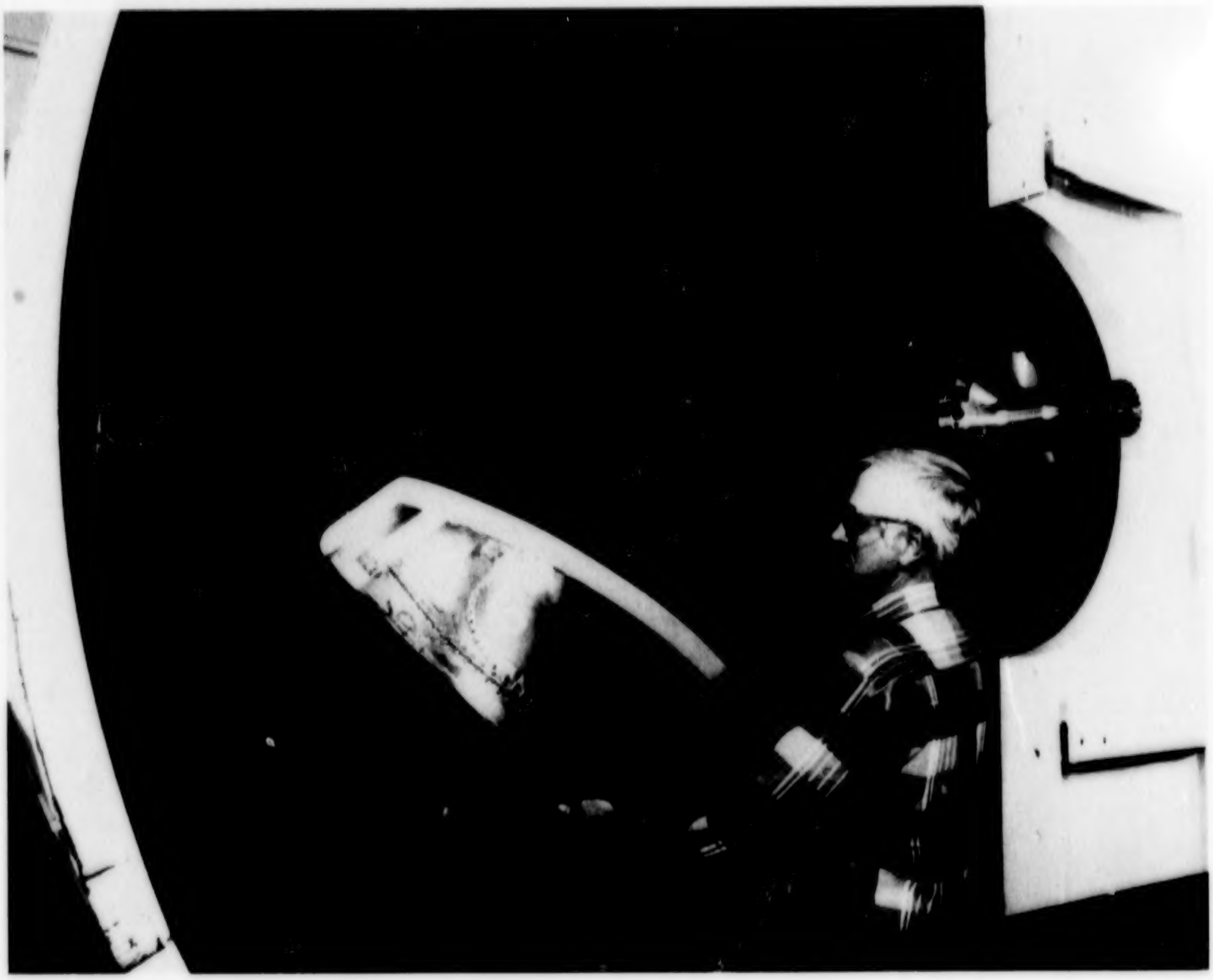


Figure 93.—Whirligig high-cycle-fatigue testing rig.

A General Electric–NASA team recommended ways to improve the bond and retain the blade shell in case of bond failure. The improvements they suggested were made to both blade rows. Before reinstallation the improved blades were mounted in the whirligig rig (fig. 93) to check their vibratory strength. They survived 3 million cycles of endurance testing to 18,000-psi vibratory stress at 1395 rpm—about 50 percent better than the original blades. These strengthened blades were installed and the test series was completed without further problems.

Ground Test Results and Conclusions

Engine testing was completed in July 1986. The UDF engine was tested for more than 100 hours, half of which was endurance testing performed in a 2-week period at the end of June to early July. On the test stand the UDF engine demonstrated 25,000 pounds of sea-level corrected thrust and achieved a specific fuel consumption of 0.24, about 20 percent better than the best turbofans available today. The UDF engine was operated over a full range of power settings, including a reverse-thrust demonstration.

A post-test teardown and inspection revealed an unscrewed locknut and some additional cracking in the turbine blading that were corrected by using a lockpin for the bearing locknut and slightly heavier damper pins on the turbine blades. Otherwise the UDF engine was in excellent shape and suitable for the proposed proof-of-concept flight tests.

UDF Flight Tests

In early 1985 General Electric approached NASA to plan a flight test of the UDF engine on a Boeing 727. The goals were to test the UDF engine in flight at altitudes and speeds equivalent to those reached by turbofans (Mach 0.8 and 35,000 feet) in order to verify the encouraging performance achieved during model testing and to determine operability under "real world" conditions.

General Electric–NASA–Boeing 727 flight tests.—For the flight test program–a cooperative venture between General Electric, Boeing, and NASA—the UDF engine was installed in place of the right-side JT8D engine on a Boeing 727 (fig. 94). The program's objectives were to obtain operability and performance data for the UDF engine over the operating envelope of the B727 and to measure far-field acoustics and community noise. Boeing also planned to install different cabin configurations in order to determine how interior modifications would affect the noise perceived by the passengers.

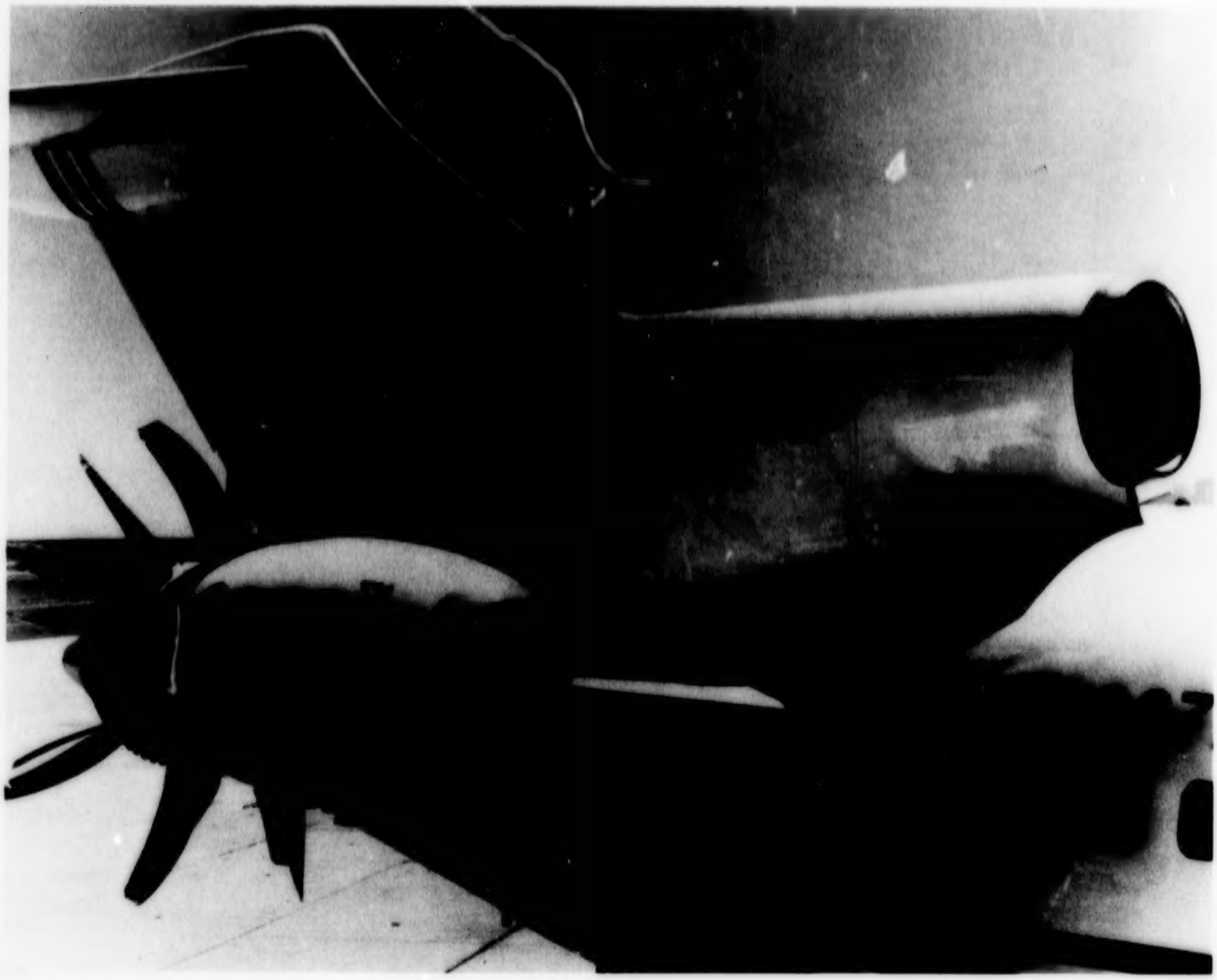


Figure 94.—UDF engine installed on Boeing 727 test aircraft.

Because this program was a step closer to a product installation, no Government funding would be involved. An agreement was signed in June 1986 stating that NASA would contribute the use of any Government-owned hardware and General Electric would modify the B727, install the UDF engine, fly the test program, and share any data recorded with NASA.

The UDF engine was shipped to the General Electric flight test facility at Mojave, California, in July 1986. Installation was completed in early August and all data systems and instrumentation were checked out by August 10. On August 14 the NASA Airworthiness Committee, consisting of Lewis and Dryden members, met at Mojave to inspect the UDF/B727 installation and to resolve any pending flight safety issues. This committee, which had reviewed the installation and aircraft modifications with General Electric and Boeing engineers, had been convened in April 1986 to ensure that all safety considerations were being addressed. Finding the final installation satisfactory, the committee considered the risk for a limited series of engine demonstration flight tests to be acceptable. They authorized General Electric to proceed on August 19.

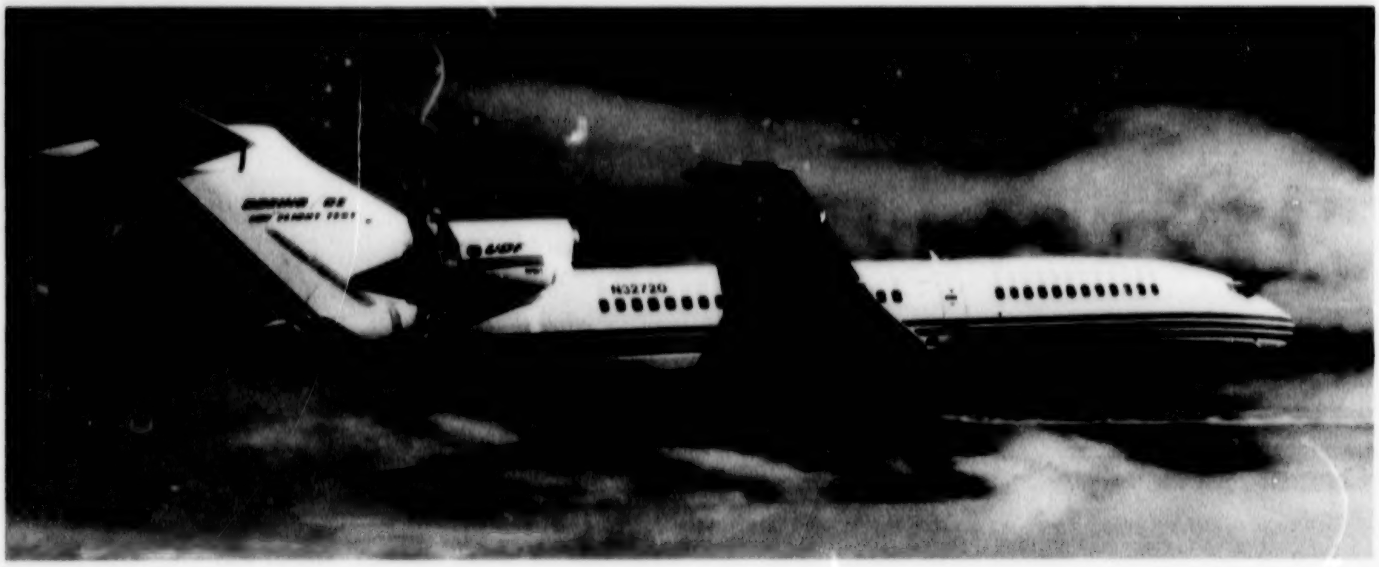


Figure 95.—Boeing 727 during UDF flight testing.

Flight testing began on August 20 (fig. 95). Over the next 6 weeks the UDF/B727 was flown to Mach 0.6 and 35,000 feet. Engine operability was good and some acoustic data were recorded, but the propeller blade stresses were somewhat higher than expected because of a two-per-revolution response to the fuselage flowfield. In order to continue testing, the blades were modified by weighting the forward-stage blades and by stripping the polyurethane coating and clipping 4 inches from the aft-stage blades. This shifted the two-per-revolution crossing for each row enough so that the full flight envelope of Mach 0.8 and 35,000 feet was flown in early December. Subsequent testing achieved Mach 0.84 and 39,000 feet without further operating difficulties.

In January 1987 acoustic tests were conducted that included flying a NASA Learjet in formation with the UDF/B727 to record in-flight, far-field noise (fig. 96). NASA recorded the data from these tests with microphones located in the Learjet nose and wingtip. The Learjet was positioned at 30°, 60°, 90°, and 120° relative to the plane of the UDF blading, and the formation was flown at altitudes to 35,000 feet. All data were shared between General Electric and NASA.

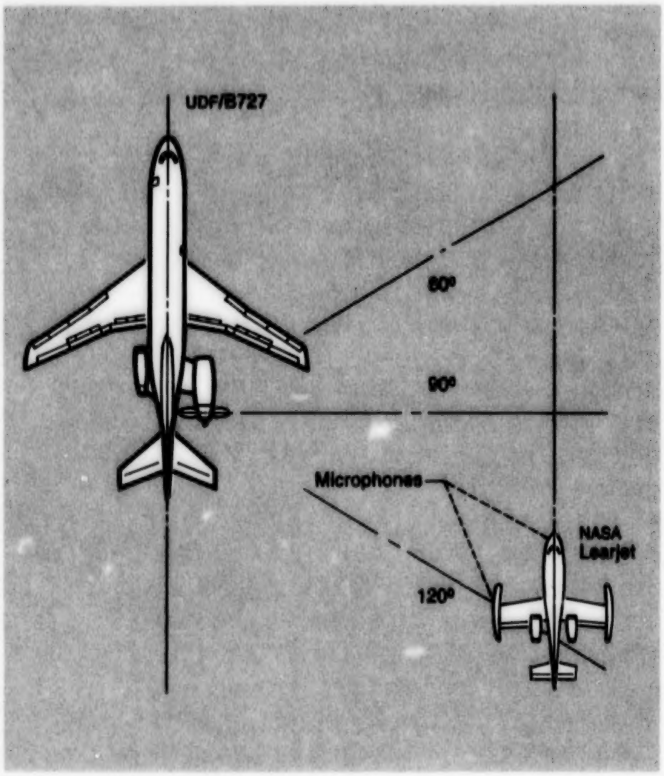


Figure 96.—Schematic of NASA Learjet and Boeing 727 acoustic flight test.

Of particular value is the comparison of flight noise data with levels projected from model data (fig. 97). The transonic wind tunnel and Learjet flight data have shown good agreement—greatly heightening confidence that any improvements demonstrated in model tests will occur in flight (fig. 98). Also shown is that the magnitude of the noise dropped as the microphones moved away from the plane of the blading. This could mean a shorter duration of sound during a flyover.

Boeing installed three experimental interior configurations during the flight test: a leaded plastic curtain over the aft pressure bulkhead, extra thick padding on the cabin sidewalls, and a cabin floor suspended on isolators. Although these measures did not afford the finished type of interior that would be pleasing to passengers, Boeing's modifications were effective in reducing noise. They were added one at a time to indicate the increment in noise reduction attributable to each measure.

The most effective reduction came from the leaded plastic curtain. Since the propfan plane is aft of the bulkhead, isolating the tail cone from the cabin reduced noise by several decibels. The cabin sidewall padding was less effective since, as indicated by skin microphones, the forward-traveling noise bounces off the fuselage boundary layer and does not penetrate the cabin walls to a large degree. The floor was partly effective in stopping structure-borne noise.

Although the blade modifications performed in the fall of 1986 made these UDF flight tests possible, the weight added to detune the forward-stage blades was not the best solution for a commercial engine. An alternative engineering approach was to build a blade with a flexible root section to avoid the two-per-revolution vibratory response. In February 1987 this blade was flown for 3½ hours to speeds over Mach 0.8 at 35,000 feet. The vibratory response was very low, and a similar design is being considered for a proposed commercial UDF in the early 1990's.

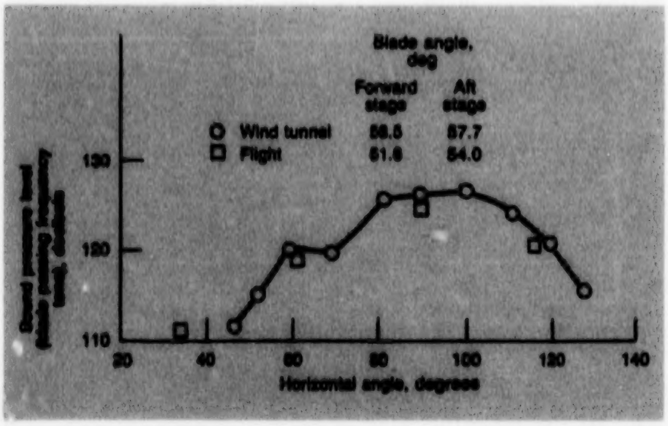


Figure 97.—UDF/Learjet acoustic flight test results compared with wind tunnel tests at Mach 0.72, 35,000 feet, and maximum climb power. Learjet wingtip microphone at 155-foot sideline distance.

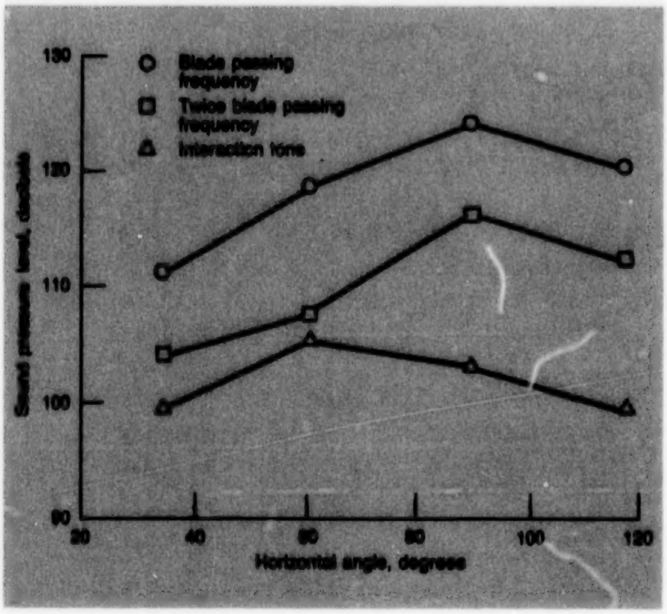


Figure 98.—Propeller tone directivity from UDF/Learjet acoustic flight tests. Forward-stage blade angle, 61.6°; aft-stage blade angle, 54°.

The flight test program for the UDF/B727 was completed in mid-February 1987. The total flight time was over 41 hours, most of which was at high-power settings (similar to those used with the JT8D on the left side). The test results showed a specific fuel consumption about 30 percent lower than that of a JT8D for the same installation (fig. 99). Enroute noise was within the climb band for existing aircraft, and the cruise noise, although slightly above average, was at a conversational level (fig. 100).

Questions about acoustics for high-speed propfans and their acceptability by the public have had some encouraging answers as a result of the UDF/B727 flight. This, plus the excellent installed fuel consumption and the ease of operation, has generated considerable interest in commercial applications.

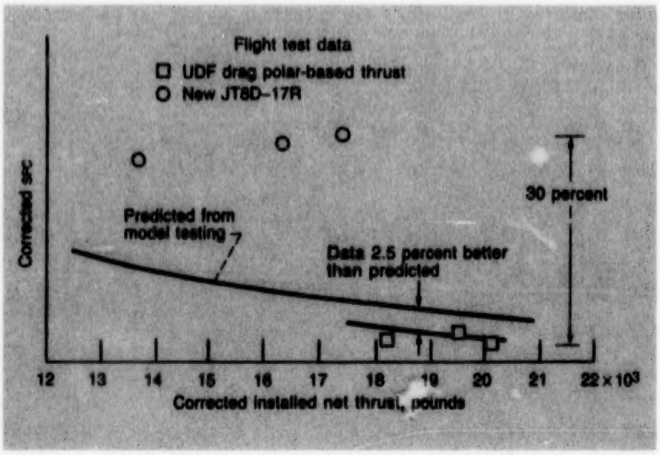


Figure 99.—UDF fuel consumption at Mach 0.8 and 35,000 feet.

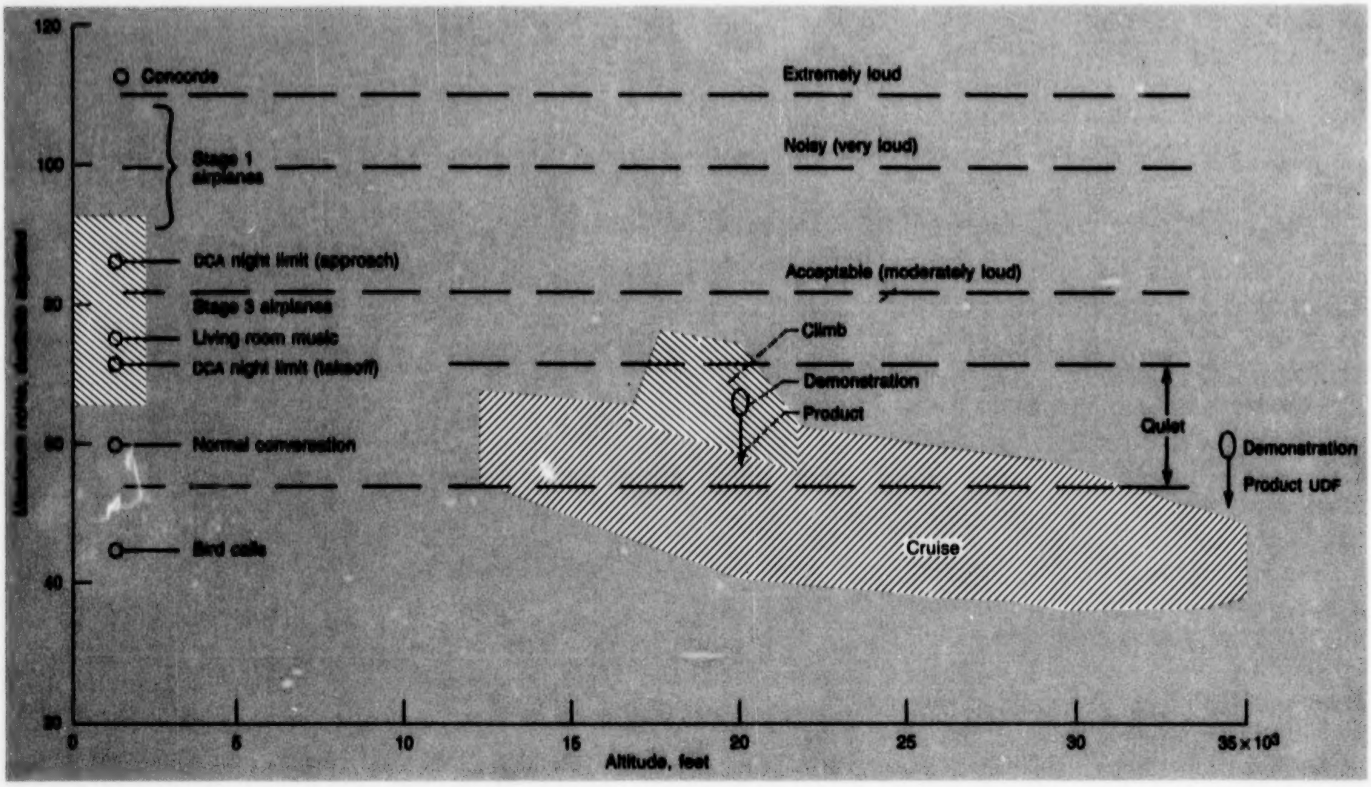


Figure 100.—UDF/Boeing 727 enroute noise levels. (Swedish data.)

General Electric–McDonnell Douglas UDF flight tests.—As a step closer to commercial acceptance General Electric and McDonnell Douglas entered into an agreement in 1986 to install the UDF engine on the left side of an MD–80 aircraft in place of a JT8D turbofan engine (fig. 101). Through flight testing they hoped to demonstrate what had been indicated in the model tests: that using more blades in the forward stage than in the aft stage can significantly reduce the noise generated by counterrotating turboprops by lessening the blade row interaction noise that results from equal blade numbers. With all other engine parameters equal, they hoped to demonstrate a 5-decibel reduction in blade passing noise for a 10- by 8-blade configuration over an 8- by 8-blade. General Electric and McDonnell Douglas planned to compare the installation effects and operability measured in these tests with the B727 flight tests by using the 8- by 8-blade engine for the initial testing and the 10- by 8-blade engine for the rest of the flight test program.

During this program General Electric provided the engine and modified the aircraft; McDonnell Douglas modified the cabin to reduce noise and made the acoustic measurements. All aircraft and cabin modifications were made with commercial use in mind. McDonnell Douglas plans to offer UDF engines on their customers' aircraft (new orders and retrofits) in the early 1990's, in order to keep their existing airframes in service, and to sell new airframes with propfan engines installed.

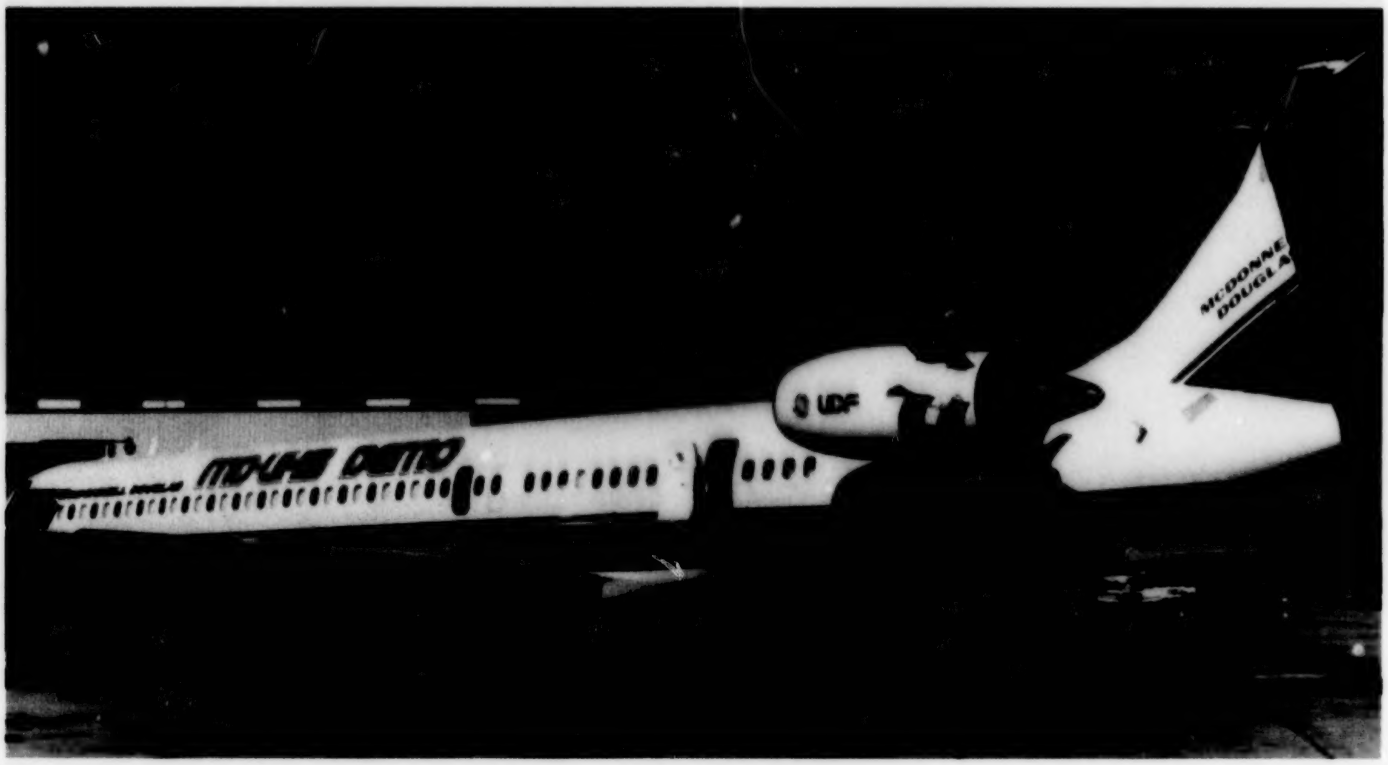


Figure 101.—UDF engine installed on McDonnell Douglas MD–80 test aircraft.

The flight test of the 8- by 8-blade UDF engine began in May 1987 and was completed by mid-July. The aircraft was flown at 35,000 feet and Mach 0.81 for a total of 40 hours (fig. 102). Engine and aircraft operability was good, and acoustic data were recorded at ground stations and in the cabin. Although the flyover noise was slightly above airline average, the interior noise was considered acceptable by engineers riding in the modified cabin.

The 10- by 8-blade UDF was ground tested on General Electric's engine stand at Peebles, Ohio, before it was installed on the flight test aircraft. It was run for 31 hours at power levels to 23,200 pounds thrust to check the propulsion package and to measure thrust and fuel consumption for comparison with the 8- by 8-blade UDF. Following the ground test series the engine was shipped to Mojave, California, for installation on the MD–80.

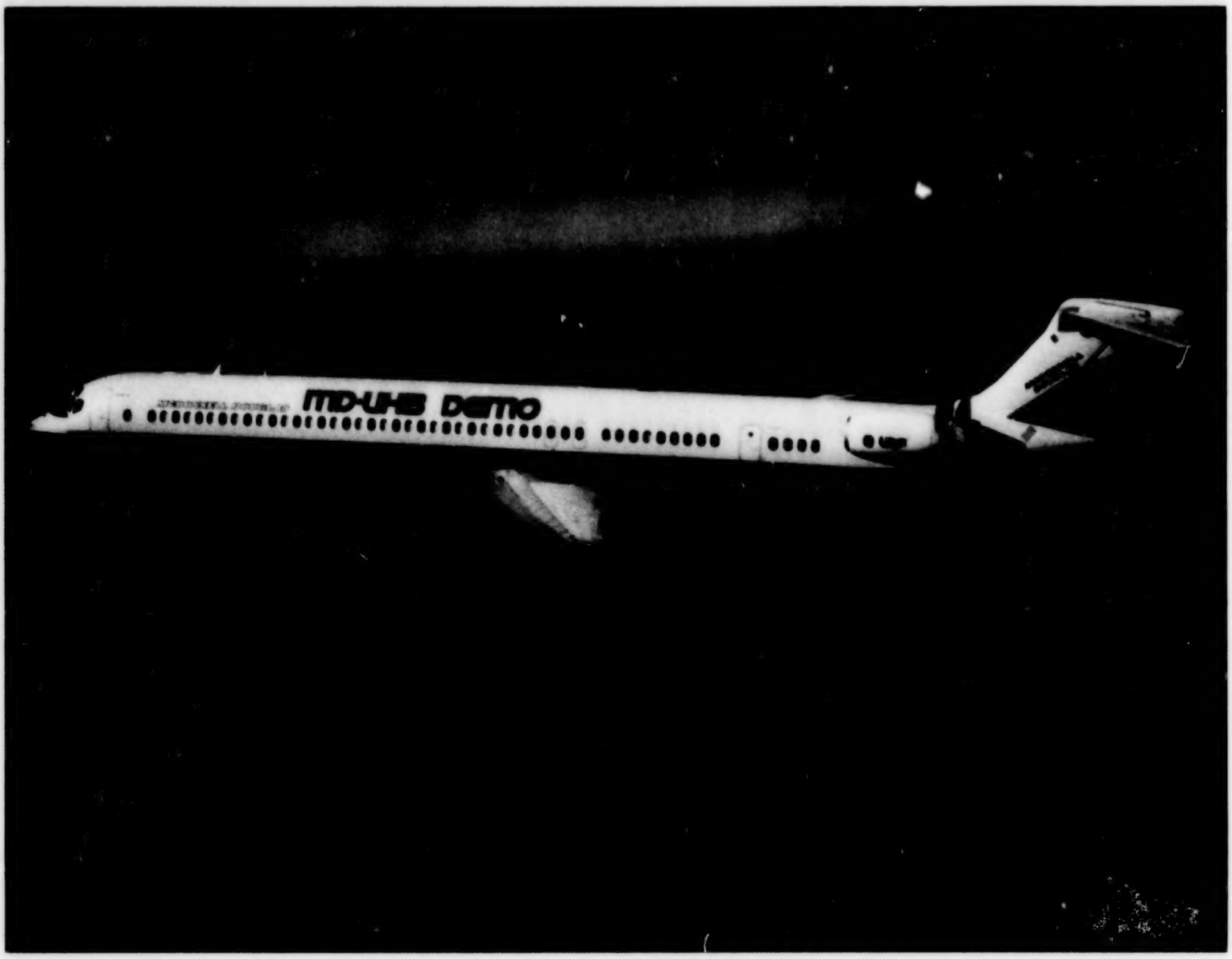


Figure 102.—MD–80 during UDF flight testing.

Flight testing of the 10- by 8-blade UDF began on August 14. The aircraft was flown over the same flight conditions as the 8- by 8-blade UDF to obtain comparative flight data. A total of 33 hours of testing was completed at altitudes to 35,000 feet over a range of power settings. Data analysis showed that the 10- by 8-blade UDF does have a slightly lower primary tone but will need improvements to be able to meet FAR–36 noise levels. General Electric is working on a commercial version of the UDF with improvements to the core engine, the actuation system, and the propfan's aerodynamic, mechanical, and acoustic design to address the problems that surfaced during the proof-of-concept tests. These improvements, combined with the acoustic cabin treatments previously demonstrated, will make the UDF engine a viable candidate for future application in commercial service.

Future Directions

The Advanced Turboprop Project has shown the turboprop's tremendous fuel-saving potential and has provided the basis for further improvement in structures, noise reduction, and fuel efficiency. To bring this technology to maturity, NASA and industry plan to continue work on turboprop propulsion concepts and the aircraft to use these new technologies. Eventually the turboprop may be used for a number of subsonic applications.

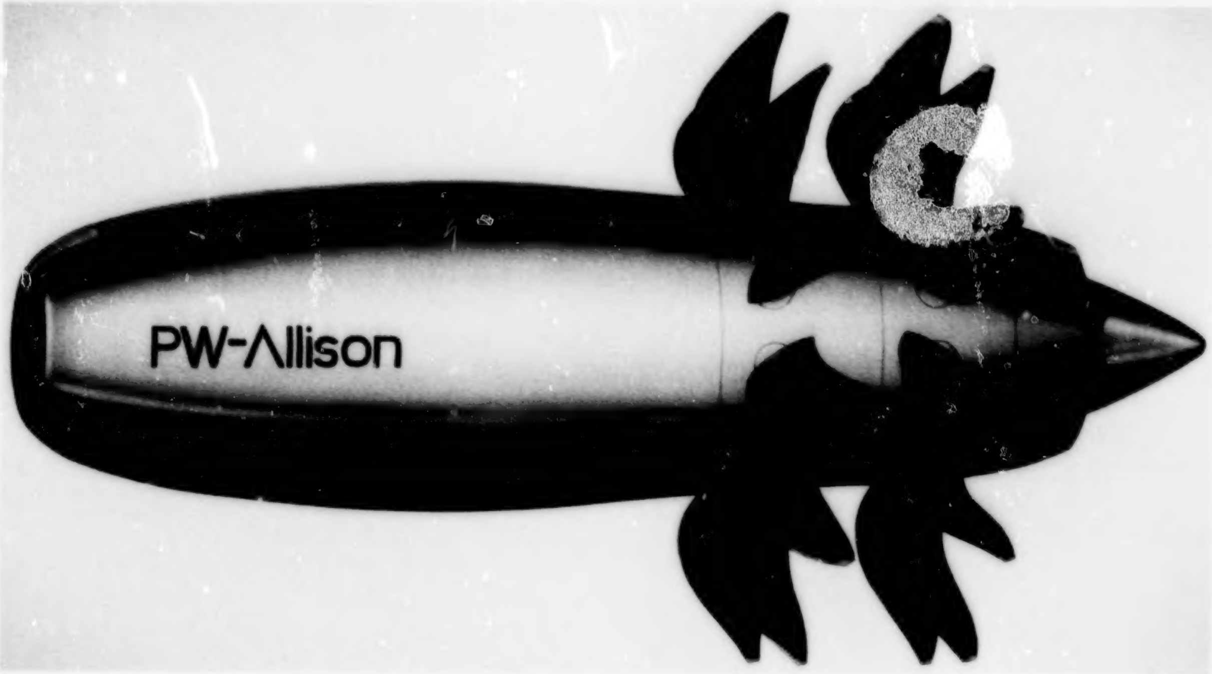


Figure 103.—Pratt & Whitney–Allison counterrotating geared propfan.

Engine Tests

Engine companies are carrying the technology ahead in order to solve problems associated with commercial applications so that they can compete effectively with foreign companies on new applications and retrofits of existing aircraft.

General Electric has planned ground tests at Peebles, Ohio, involving bird ingestion, lightning strikes, and icing of the propfan blades. These tests will be done as a cooperative effort with the Government to determine baseline data for engine certification. General Electric plans to install an Unducted Fan (UDF) engine on a Boeing 727 in 1990 for flight demonstration and certification. Their intent is to have a commercial UDF available with an advanced core and quiet-technology propfan blades by 1992.

Pratt & Whitney and Allison are presently cooperating on a geared pusher counterrotation propfan. They believe that the gears in their propfan will provide a lighter turbine and a more efficient match of turbine and propeller rotational speed with a smaller diameter nacelle. By using gearbox technology developed in conjunction with NASA they hope to avoid the gearbox problems of early turboprops and to show a 4 to 6 percentage point saving in fuel over the UDF. Pratt & Whitney–Allison plan to test the engine shown in figure 103 on the MD–80 in early 1988 for a direct comparison with the UDF performance. They expect to have a commercial version of their engine certified in 1992.

NASA Research

NASA's goal in this program has been to provide the technology base to enable U.S. industry to develop quiet, fuel-efficient turboprop engines that will allow a comfortable aircraft interior environment. In doing so, NASA has generated a considerable amount of information related to advanced propfan technology. Striving to further understand the physics involved in turboprops, NASA will continue a strong research program in propfan aerodynamics, acoustics, and aeroelastics to improve efficiency, to reduce noise, and to better predict blade stress and stability boundaries.

NASA plans to study the interaction between the stages of counterrotating systems, to develop structural methods for designing blades with greater sweep, to obtain data on higher cruise speed designs and smaller diameter propellers with higher loadings, and to determine effective ways to recover single-rotating swirl with a coupled downstream vane section. Tests will be conducted in NASA wind tunnels and the results used to validate and improve design codes.

To develop more efficient aircraft with even higher fuel savings, NASA Ames and Langley will work on acoustics and installation effects, the aircraft interior environment, and the packaging of propfan propulsion systems with the aircraft.

Research on a ducted propfan is also planned. The ducted propfan will have a smaller overall diameter than the unducted propfan but the same thrust, which will allow easier installation of wing-mounted engines. Aerodynamic, acoustic, and aeroelastic codes will be based on a synthesis of propfan and turbofan analytical methods. The modified codes will be based on low-pressure-ratio, low-solidity turbofans or high-speed, higher loading turboprops. Analytical results will be verified in tunnel tests of single- and counterrotating models with thin, short-duct nacelles. Selected advanced concepts will be evaluated for fuel consumption, noise, and structural stability relative both to an equivalent propfan engine and to an advanced turbofan engine.

Aircraft of the 1990's

Several aircraft concepts are being considered for the 1990's. Some would replace the engines on airframes presently in service with turboprops. Others are fresh airframe designs specifically for turboprop installations. Figure 104 shows a Boeing design planned as a new aircraft specifically for a turboprop installation. Figure 105 shows a reengined MD–80, which may be redesignated as the MD–91X. Figure 106 shows a possible wing-mount installation for a smaller commercial transport. The military cargo aircraft shown in figure 107 is a wing-mounted, counterrotating heavy-lift design. These designs are being considered. Whether they are put into service depends on the aircraft market at the time the engines are certified.

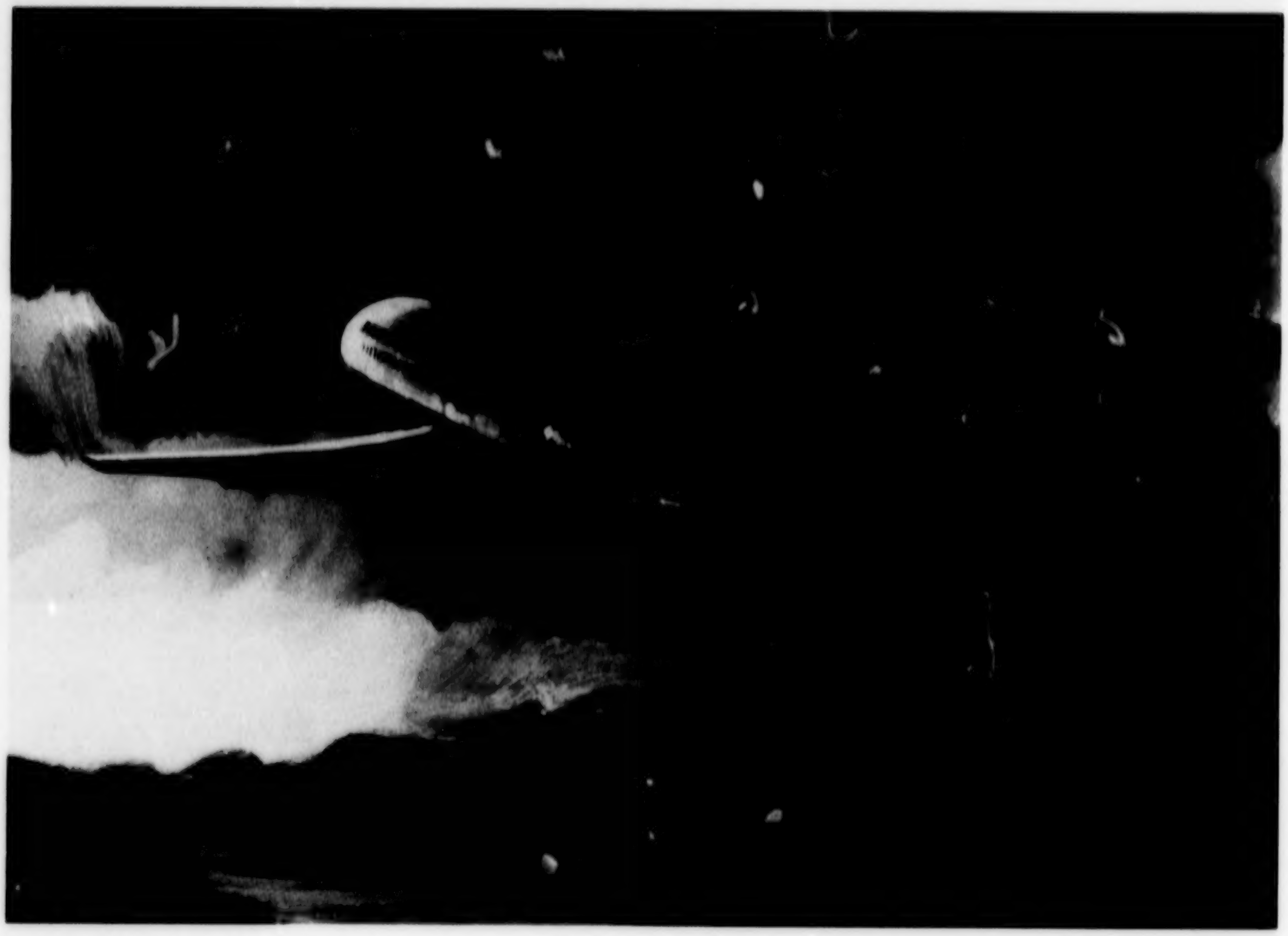


Figure 104.—Boeing 7J7 aircraft.

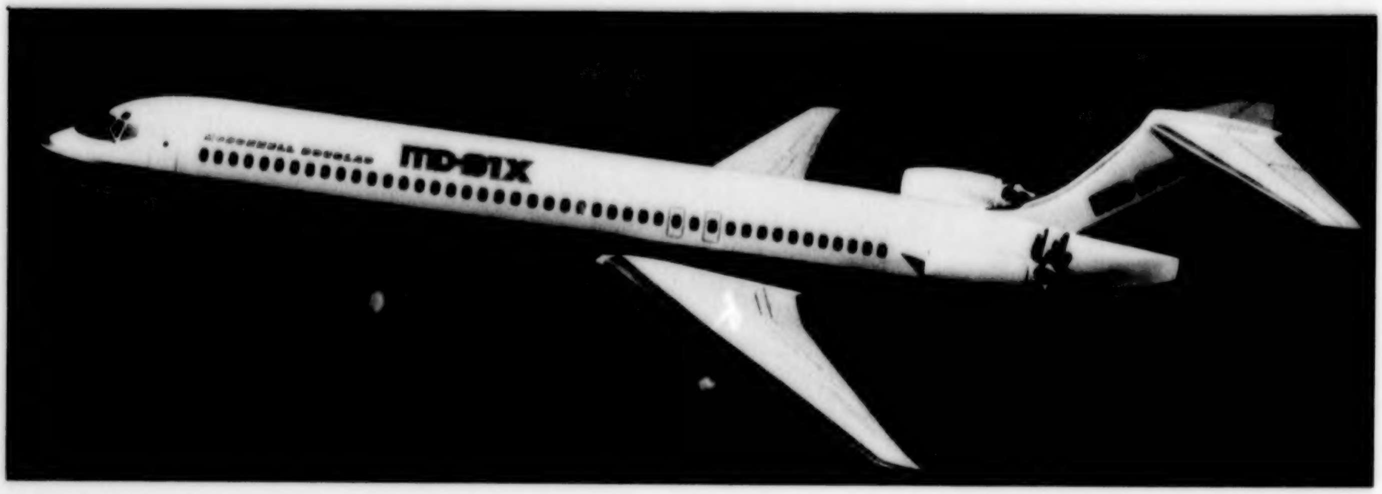

MCDONNELL DOUGLAS
MD-91X

Figure 105.—McDonnell Douglas MD–91X aircraft.

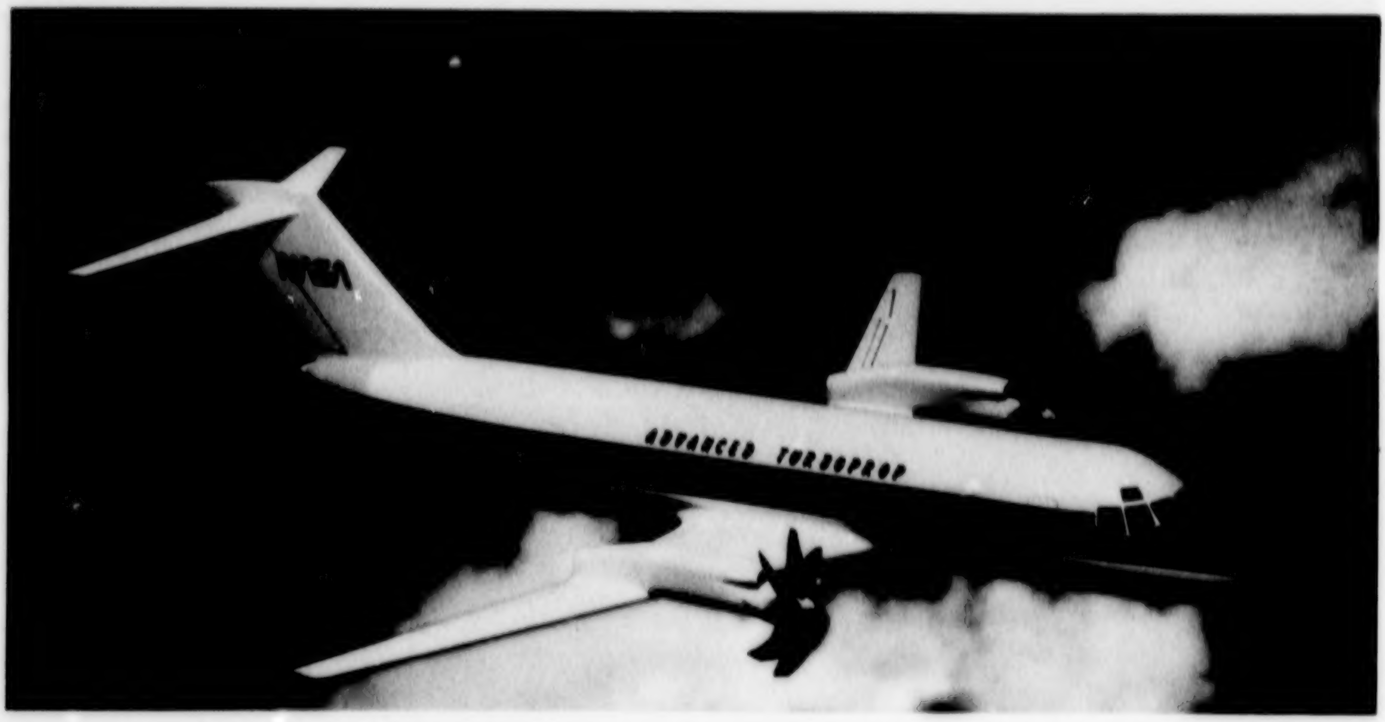

NASA
ADVANCED TURBOPROP

Figure 106.—Single-rotation, wing-mount commuter aircraft.

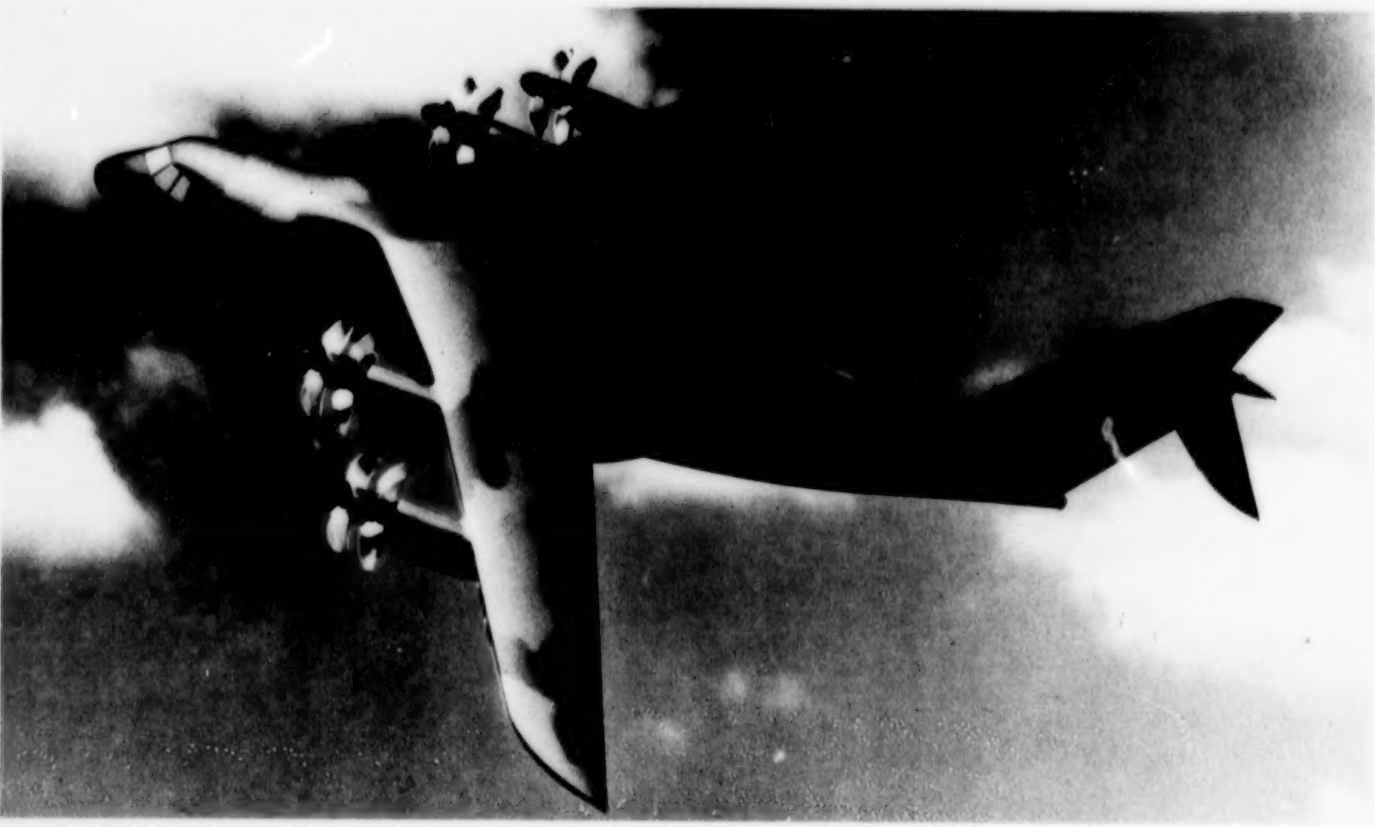


Figure 107.—Counterrotation, wing-mount military transport aircraft.

Concluding Remarks

During the life of the Advanced Turboprop Project a dedicated NASA–industry–university team brought turboprop technology from its infancy in the early 1970's to a successful demonstration on three separate flight tests. As shown in figure 108 flight tests have been conducted with advanced turboprop engines on the Boeing 727 and the McDonnell Douglas MD–80 in a commercial flight environment and on the PTA Grumman Gulfstream II aircraft to record acoustic, aerodynamic, and aeroelastic data for design code verification.

Studies, model tests, and flight tests have shown that turboprops with thin, swept, highly loaded blades can operate at high speeds (Mach 0.65 to 0.85) and reduce block fuel consumption 25 to 30 percent relative to advanced turbofans (40 to 50 percent relative to today's aircraft). To put these numbers in perspective, the B727, B737, DC–9, and MD–80 portion of the U.S. passenger fleet could save 2.5 billion gallons of fuel each year (fig. 109) if the existing low-bypass-ratio JT8D engines were replaced with advanced turboprop engines having the latest in core technology.

The technology developed by the ATP Project promises to revolutionize the aircraft industry and will give the United States an enormous advantage in the worldwide marketplace. Projections show that late in this century a new market for 2000 to 4000 aircraft will be waiting to be filled (fig. 110). As commercial turboprops become available, the U.S. aviation industry could earn $50 billion to $100 billion by selling these aircraft to the domestic and foreign markets.

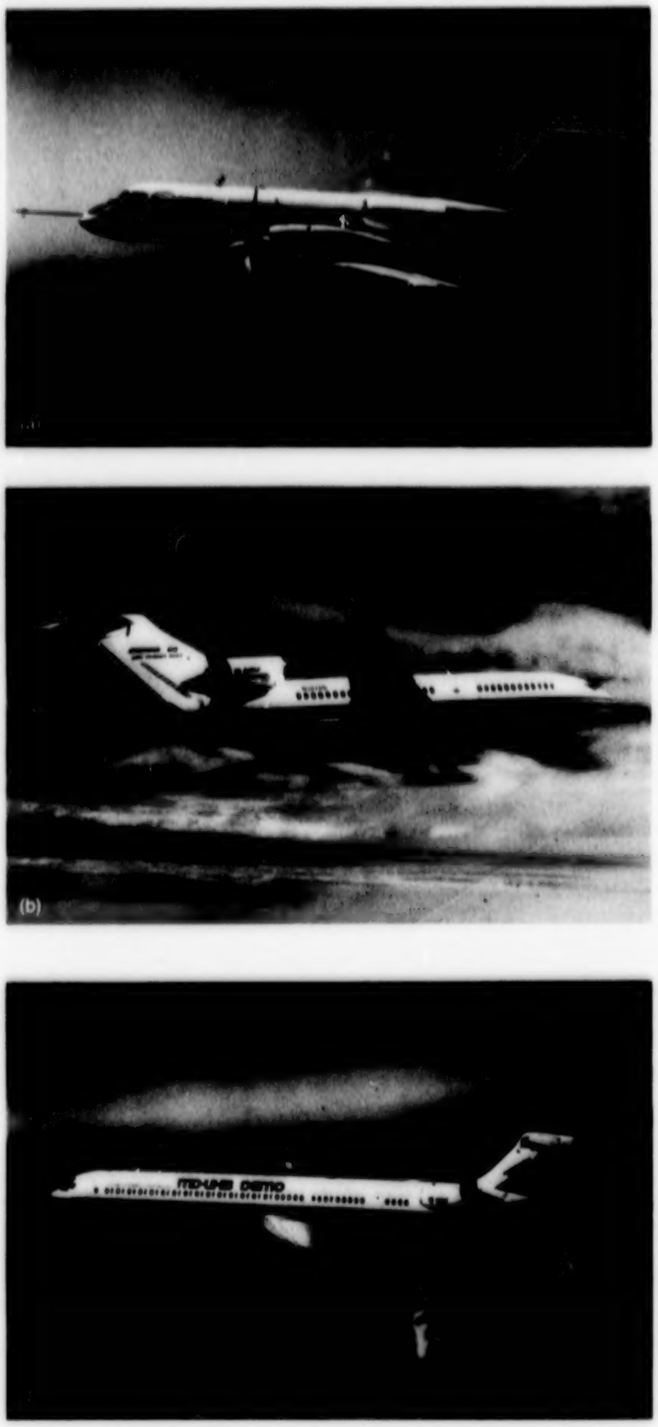


Figure 108.—ATP flight test aircraft. (a) PTA on Grumman Gulfstream II. (b) UDF on Boeing 727; (c) UDF on MD–80.

The advanced turboprop promises major reductions in the direct operating costs of future subsonic commercial transport aircraft, and as fuel prices rise the impact will become greater. All aircraft, whether a medium-range, wide-body transport with four wing-mounted engines, a long-range military patrol aircraft, or a business/commuter aircraft with a single-rotating engine, will benefit from the technology developed by the Advanced Turboprop Project.

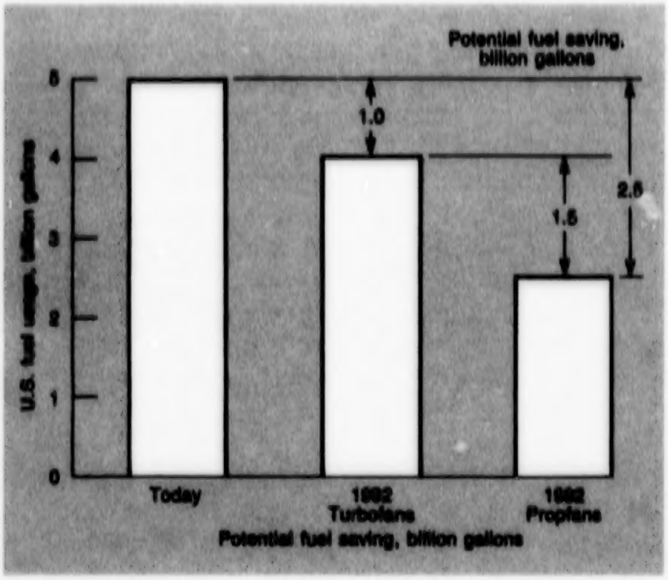


Figure 109.—Potential fuel saving for U.S. B727, B737, DC–9, and MD–80 fleet.

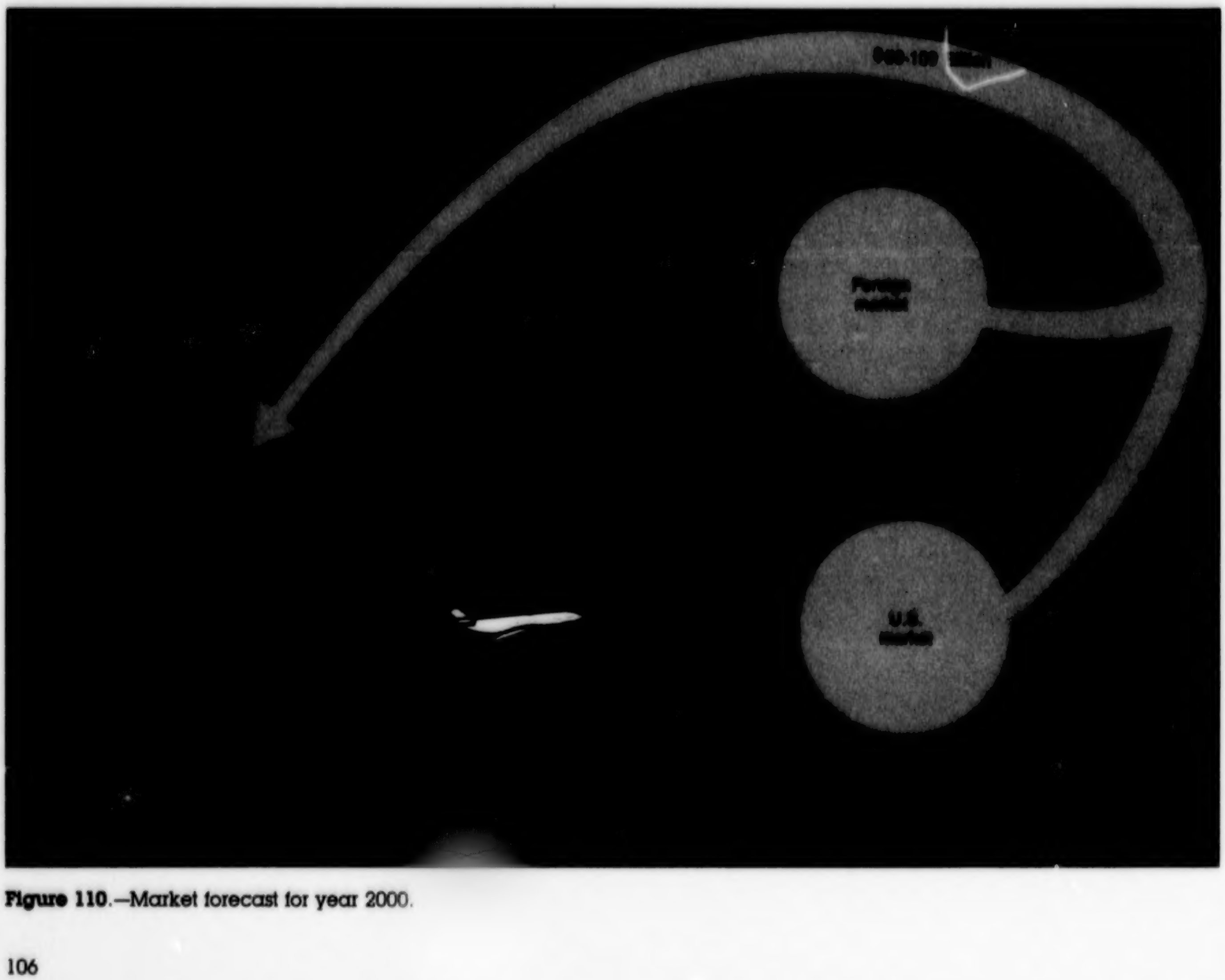


Figure 110.—Market forecast for year 2000.

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Entries are arranged in chronological order within each subcategory.

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